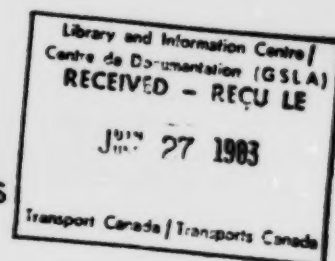


1981/82 ACIB EVALUATION
DATA COLLECTION AND ANALYSIS



TP 4086E

March 1983

by

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17. Abstract This project was carried out to evaluate the performance of an air cushion icebreaking platform (ACIB). The trials were conducted first with the ACIB alone to evaluate its heave characteristics, then was attached to the Alexander Henry icebreaker where icebreaking tests were conducted five kilometres east of Thunder Bay harbour. An instrumentation package was installed on the ship and the ACIB where continuous recording of the cushion pressure, thrust and torque of the propeller shafts and other important parameters were made. In this report, the results and their analyses are presented. Comparison with results of previous experiments conducted with the air cushion transporter ACT-100 was also made. A preliminary estimate for the main requirements of an Arctic Air Cushion Vehicle was made.			
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17. Résumé Ce projet a été effectué afin d'évaluer la performance d'une plate-forme à coussin d'air conçu spécialement pour briser la glace. Les essais ont commencé par l'évaluation des caractéristiques principales de la plate-forme seule. Par la suite, la plate-forme a été attachée au brise-glace 'Alexander Henry' pour des essais de déglacage effectués au port de Thunder Bay. Un système d'acquisition des données a été installé sur la plate-forme et le brise-glace afin d'obtenir continuellement la pression du coussin d'air, la poussée et le couple sur l'arbre des hélices, ainsi que d'autres paramètres importants pour l'évaluation du système. Dans ce rapport, les résultats ainsi que leur analyse sont présentés. La comparaison des résultats avec d'autres essais similaires utilisant le transporteur à coussin d'air ACT-100 a été faite. Un estimé préliminaire des caractéristiques d'une plate-forme de classe arctique a été fait.			
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NOMENCLATURE

H	Hoverheight	$\rho_w g$	Specific weight of water
H_f	Flotation Tank Depth	$\rho_i g$	Specific weight of ice
H_c	Tank Bottom Clearance	B	Ship, ACIB, ACT-100 beams
P_c	Cushion Pressure	K_p	Pitch stiffness
B_t	Ballast Weights	K_{PN}	Pitch stiffness on cushion
α	Pitch Angle	K_{PF}	Pitch stiffness off cushion
β	Roll Angle	K_R	Roll Stiffness
P_m	Pitch Moment	K_{RN}	Roll stiffness on cushion
R_m	Roll Moment	K_{RF}	Roll stiffness off cushion
h	Ice Thickness	d	Cantilever Beam Length
ψ	Freeboard of ice $(\rho_w g - \rho_i g)h$	Ker'	Mathematical function (Reference [17])
δ	Deflection		
ϵ	Air gap below the ice cover		
μ	Friction Factor		
σ	Flexural Strength		
E	Modulus of Elasticity		
a	Approximate radius of ACIB (12 m)		
t	Thrust deduction factor		
R_i	Ship ice resistance		
L	Ship and ACIB Length		
R_A	ACIB Resistance		
T	Ship Thrust		
D	Draft		
V	Velocity		
∇	Displacement		

1. INTRODUCTION

1.1 Overview

Since the beginning of the last decade, several full scale and model scale trials have been conducted to investigate the feasibility, performance and effectiveness of an air cushion icebreaking bow.

The use of an air cushion vehicle as an icebreaking system was recognized in the winter of 1971/72 in Yellowknife when the air cushion transporter ACT-100 broke ice while being towed at a relatively low speed across the Great Slave Lake, Ball [10]. A second trial in Tuktoyaktuk Harbour confirmed the observation found in earlier tests and provided better understanding of the mode of ice failure and the cushion pressure/ice thickness relationship. Other tests followed in Montreal Harbour and Toronto Harbour with the Terracross H-119 towed air cushion raft and the Hover Jack. During the experiments with the self-propelled air cushion vehicle "Le Voyageur" at Parry Sound, two modes of icebreaking were observed. The first one occurred when the ACV was moving at low speed. This mode of failure breaks the ice by introducing an air cavity under the ice cover which causes the ice to fail due to its own weight. When a certain critical speed was exceeded a second mode of failure occurred. The ice failed at the crest of the wave generated by the ACV.

In 1975, Transport Canada set up a comprehensive plan to develop a low speed air cushion icebreaking platform that could be notched to the bow of a ship. The goal of the program was to improve the icebreaking capability and effectiveness for any ship with the addition of the Air Cushion Bow.

The first full scale trials were conducted during the winter of 1975-76. The CCGS ALEXANDER HENRY was used to push the Air Cushion Transporter ACT-100. The success of the experiments was evident when the ship, which could hardly break 0.3 metres of ice continuously, became capable of breaking up to 0.75 metres of ice continuously. A second trial was conducted in the winter of 1976/77. The ACT-100 was attached to an ice class tanker "ST CLAIR" and to the CCGS GRIFFON. The results were very encouraging and confirmed the effectiveness of a removable icebreaking bow.

The accumulated research studies conducted during these experiments and a series of model scale tests contributed to the design of the Air Cushion Icebreaking Bow (ACIB), which was built by Hoverlift Systems and was tested in late winter 1982. This report presents the results of these experiments.

1.2 Objectives

The overall objectives of this project were to test and evaluate the Canadian Coast Guard Air Cushion Icebreaking Bow during the 1981-82 winter season.

The tests consisted of hover tests over land and water of the ACIB alone, to determine the basic operating characteristics of the craft, and trials over ice to evaluate the icebreaking performance of the ACIB/HENRY system in various ice conditions.

The work included the design and set up of a data collection system which would permit analysis of major parameters influencing the performance of the ACIB before and during testing.

1.3 System Description

1.3.1 The ACIB

The Air Cushion Icebreaking Bow designated ACIB-HSL 533, is a diamond shaped platform, the aft end is notched to allow attachment to the ship. The attachment system allows freedom to heave and pitch, and at the same time provides a good seal against the pressure under the platform. The ACIB geometry and characteristics are shown in Figures 1.1 and 1.2.

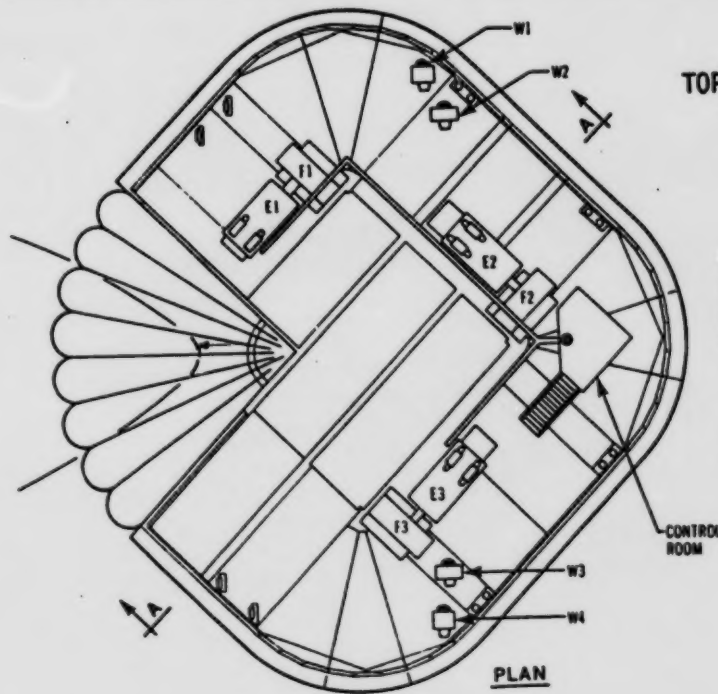
1.3.2 CCGS ALEXANDER HENRY

The characteristics of the icebreaker CCGS ALEXANDER HENRY, used for the present tests, are shown in Table 1.1. The two vehicles were attached with a cable pretensioned to 8 tonnes to minimize the motion of the ACIB relative to the HENRY.

1.3.3 Icebreaking

The basic icebreaking principle of the system consists of providing a cushion pressure under the ACIB platform (Figure 1.3). That pressure, when larger than the ice thickness (in equivalent water depth), allows the progression of an air cavity under the ice. This cavity causes the ice to fail under its own weight. Since the ice requires much less force to fail by bending than by crushing, the overall energy requirement to break in similar ice conditions is therefore less, which has been confirmed by previous experiments with the ACT-100 in Thunder Bay.

FIGURE 1.1
TOP VIEW OF ACIB

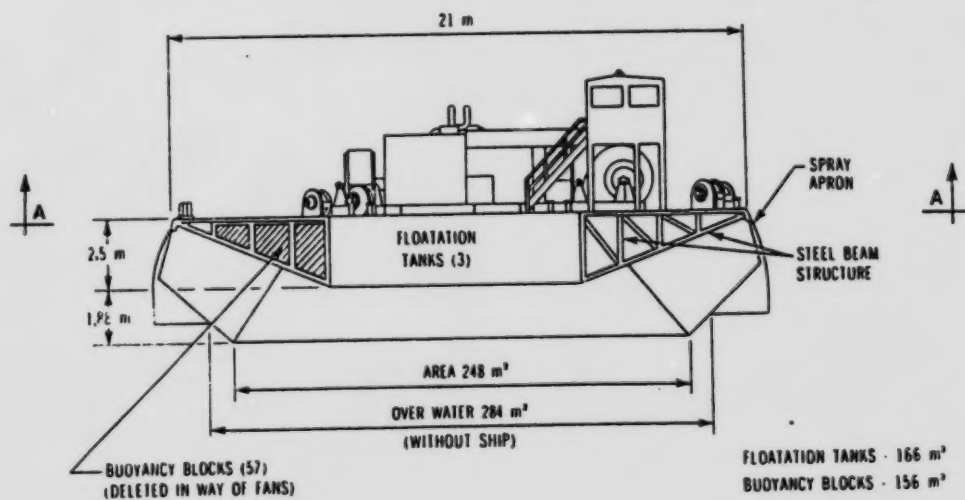


ACIB - HSL 533

WEIGHT	CUSHION PRESSURE
MAX. 270 t	10 kPa
MIN. 180 t (166.2 md)	6 kPa
CUSHION AREA 284 m ² (unnotched)	
OVERALL BEAM 24.7 m	
CUSHION BEAM AT 10 kPa = 22.6 m	
W1, W4 - NOTCHING WINCHES = 100 kW	
W2, W3 - TRANSIT WINCHES = 60 kW	
E - ENGINES (3), EACH 490 kW	
F - FANS (3), EACH 85 m ³ /s AT 10 kPa	

FIGURE 1.2
SIDE VIEW OF ACIB

ACIB - HSL 533



SECTION A - A

TABLE 1.1
CCGS ALEXANDER HENRY DATA

DIMENSIONAL PARAMETERS

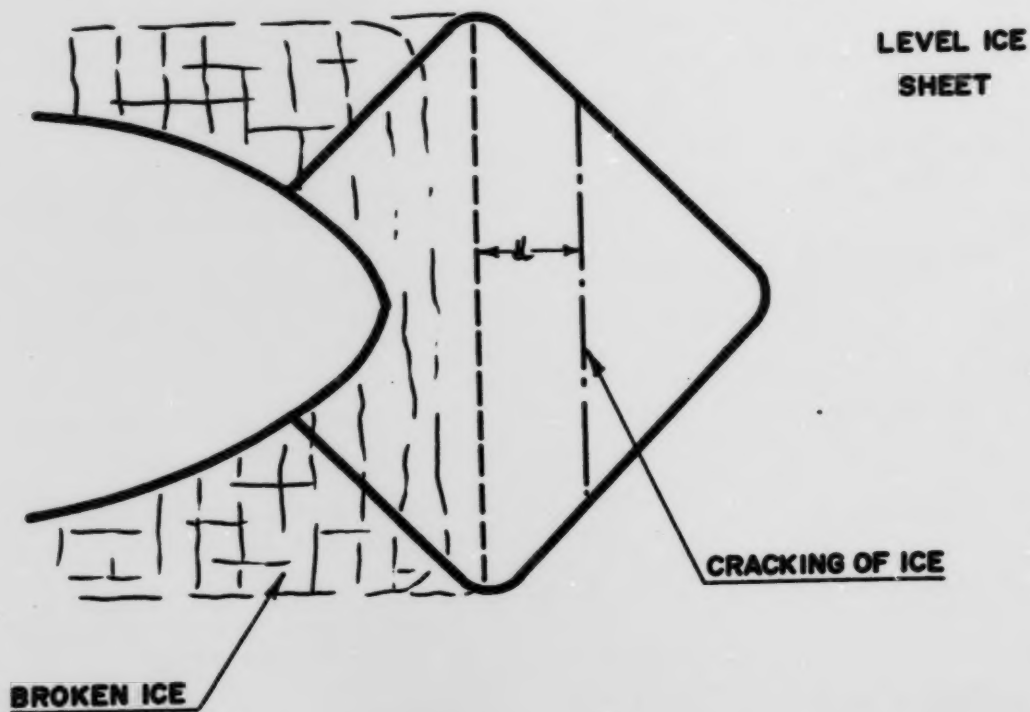
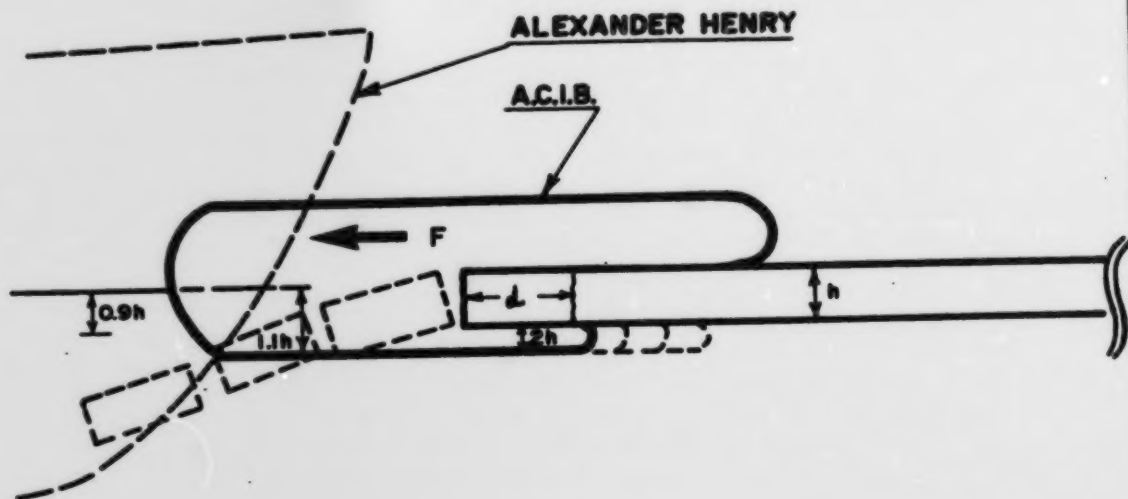
Length $L = 64.10$ m
Beam $B = 13.26$ m
Draught $D = 5.86$ m (maximum)
Displacement $\nabla = 3195.5$ tonnes (maximum)

DIMENSIONLESS PARAMETERS

$L/B = 4.81$
 $B/D = 2.27$

FIGURE 1.3

PRINCIPLE OF OPERATION OF
AN AIR CUSHION ICEBREAKING BOW



2. SCOPE OF WORK

The tests were conducted in Thunder Bay Harbour between the months of February and April, 1982. This was over a month later than the original schedule of these field trials.

The program consisted of over land and over water hover tests on the ACIB followed by icebreaking tests using the ALEXANDER HENRY (See Table 2.1 below). The tests consisted of measuring the stiffness characteristics of the ACIB in pitch, roll and heave. The cushion pressure for various RPM and dead weight combinations were also investigated so that design specifications of the craft could be correlated to the actual performance.

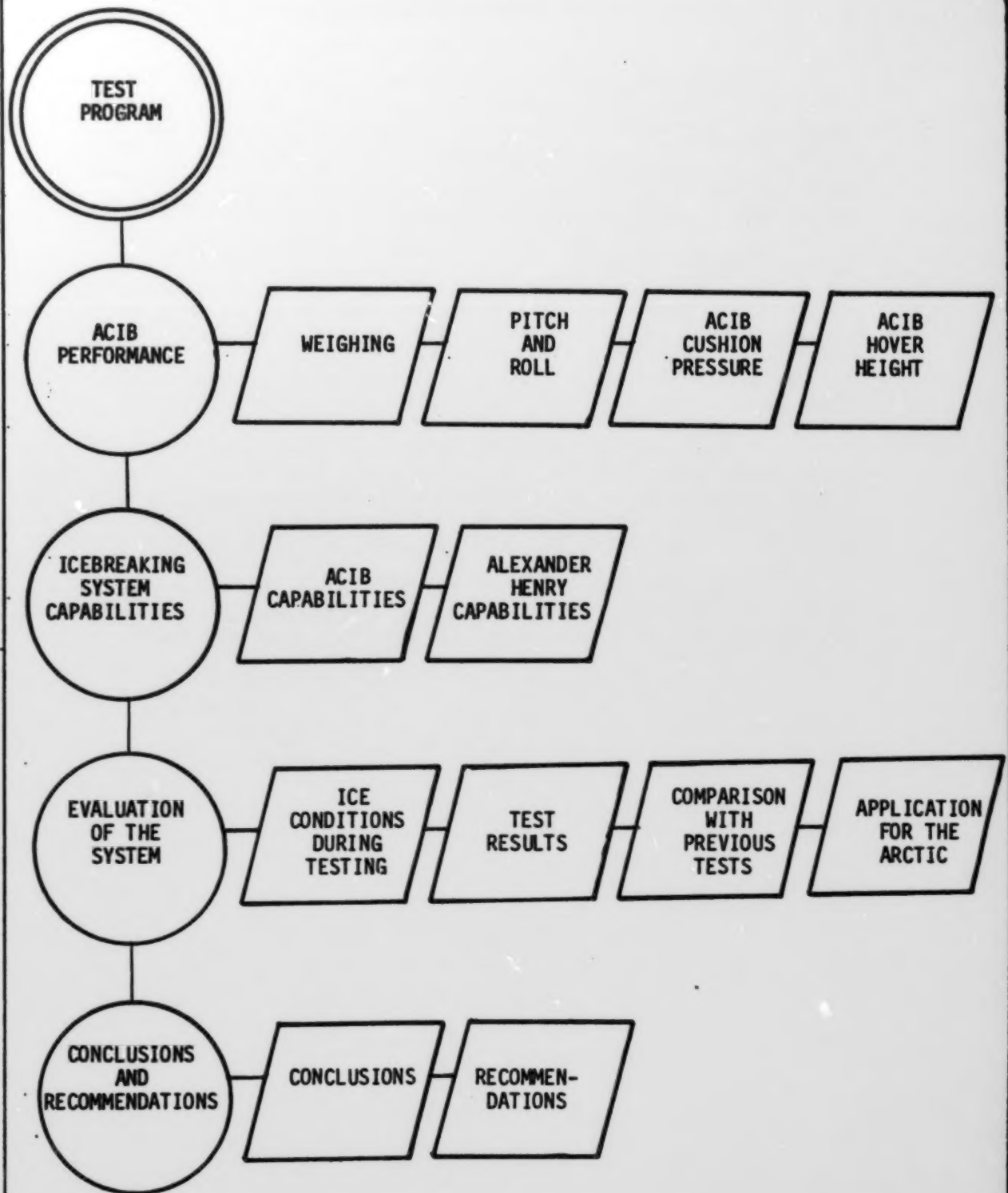
The icebreaking tests with the ACIB/ALEXANDER HENRY System were conducted between April 22 and 29, 1982. The ice was weak and disintegrating in some areas. Therefore, most of the icebreaking tests were conducted in relatively similar ice conditions. During the icebreaking tests, the resistance of the ACIB alone while moving over ice and the thrust of the system during icebreaking were measured so that comparisons to previous experiments conducted with the ACT-100 could be made.

Figure 2.1 presents the steps considered for reporting the results of these trials and their analyses.

TABLE 2.1
SUMMARY OF THE TEST PROGRAM

TEST	DATE	DESCRIPTION
WEIGHING	27 Feb 82	Total weight of ACIB was measured
ACIB ALONE		
- over land	13-31 Mar	Non dedicated tests - cushion pressure and hover height.
- over water	14-16 Mar	Dedicated tests to measure pitch and roll stiffness, cushion pressure, and hover height of ACIB
- over ice	16 Apr	First notch test with 16 tonnes ballast weight
	22 Apr	Second notch test with full ballast weight
ALEXANDER HENRY alone	During March	Measure thrust, rpm, torque to obtain a data base on ALEXANDER HENRY icebreaker alone
ALEXANDER HENRY With the ACIB	22,23 And 29, Apr 82	Icebreaking tests. Over 50 runs. Six selected runs with over 100 m of penetration were used for analysis.

FIGURE 2.1
OVERVIEW OF TASKS



3. THE AIR CUSHION ICEBREAKING BOW (ACIB) PERFORMANCE

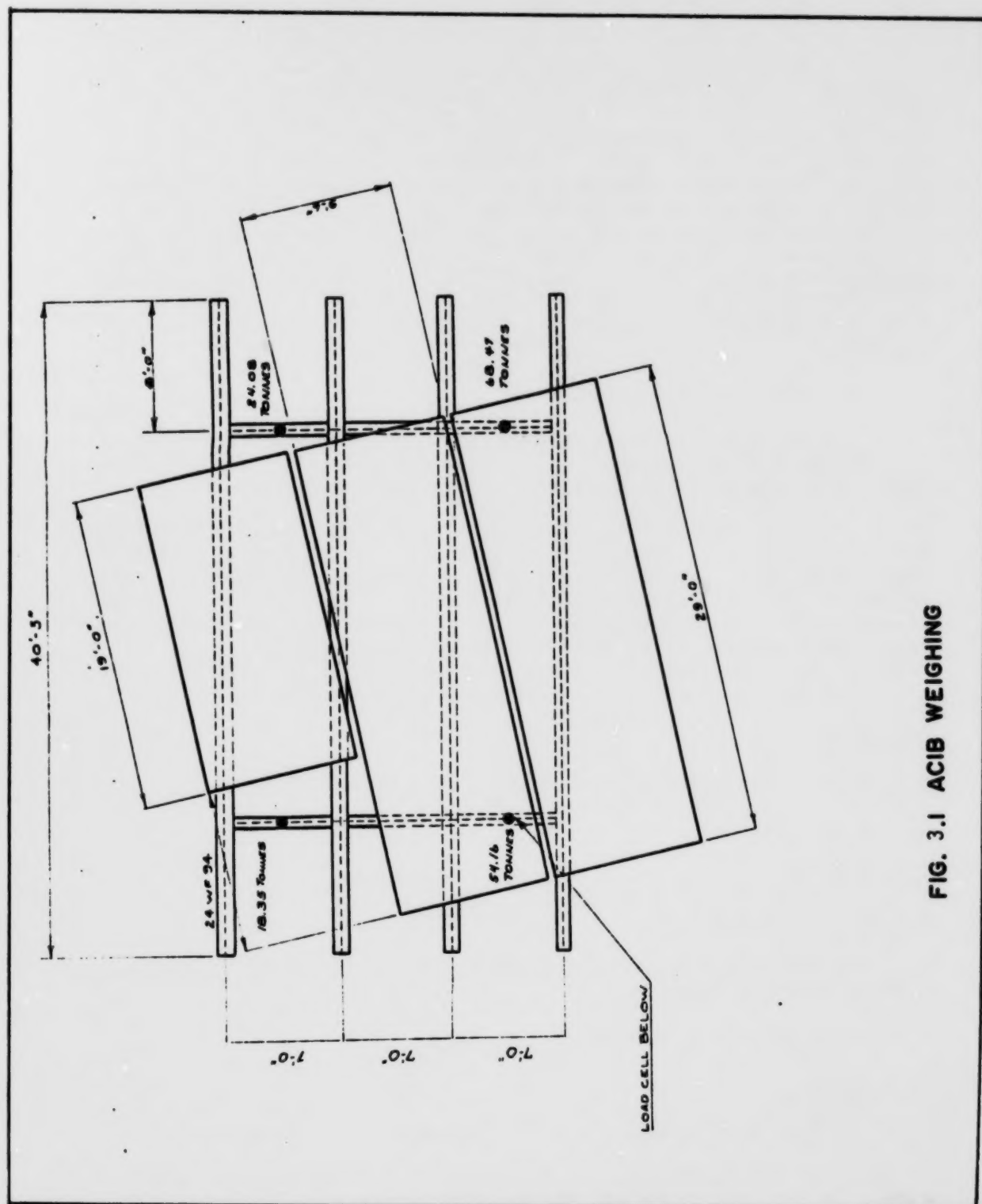
Extensive tests were conducted on the ACIB alone, before being attached to the ALEXANDER HENRY. These tests started in March and were completed mid-April. The tests include weighing of the ACIB and measuring the pitch and roll characteristics of the craft by introducing various pitch and roll moments at different RPM levels both over land and in water. As well measurements of actual cushion pressures versus engine RPM and ballast weight were made.

3.1 ACIB - Weighing

The Air Cushion Icebreaking Bow (ACIB) was weighed on the evening of February 27th, 1982. The weighing was accomplished by constructing a supporting frame which held the ACIB at four points (see Figure 3.1). A force block was placed at each of these points. The total load was the algebraic sum of the four load cell outputs.

Three of the load cells used had a capacity of 136 tonnes each while the fourth had a 45 tonne capacity. Four Vishay strain gauge signal conditioners and a digital volt meter were used to read the output signal. The calibrations of these load cells were performed prior to testing, at the National Research Council of Canada.

The measured weight of the ACIB after taking into consideration the supporting frame (8 tonnes) and adding the weight of the missing segments (8.9 tonnes) was 166.2 tonnes, (365,685 lbs).



3.2 ACIB Pitch and Roll Tests

A dedicated series of pitch and roll tests over water was conducted at Port Arthur Shipyard in Lakehead Harbour during the period of April 14 to 16, 1982. A total of twenty-one tests were conducted in which four load increments were applied starting with 15.9 tonnes and concluding with 88.9 tonnes. For each load increment four to nine different pitch and roll moments were applied by moving the weights fore and aft or side to side on the ACIB platform. In Appendix D, a detail of the load locations as well as the calculations of the applied pitch and roll moments are given. The test results are summarized in Table 3.1 showing the ballast weight, the pitch and roll moments, the pitch and roll measured angles for both on cushion (all three engines at 1800 RPM with the exception of tests 1 - 3 which were at 1500 RPM) and off cushion.

3.2.1 Pitch Stiffness

The pitch stiffness is required so that the pitch angle can be set for any ballast condition. The results of the pitch tests showed significant dependence of the pitch stiffness on the ballast weight.

Pitch moment and pitch angle have been plotted for four ballast conditions, for both the on-cushion and off-cushion conditions (see Table 3.1, Figure 3.2 and 3.3). The pitch stiffness is the reciprocal of the slopes of the plots shown. Clearly for a given ballast condition the stiffness is linear, however for the on-cushion case, the stiffness is a function of the ballast weight. In the off-cushion condition the stiffness is not a function of ballast, at least for the range of ballast shown. The stiffnesses are:

On-Cushion

$$K_{p1} = 23.25 \text{ (tonne-meter/degree) for } B_t = 15.9 \text{ tonnes}$$

$$K_{p2} = 26.31 \text{ (T-m/deg) for } B_t = 44.7 \text{ tonnes}$$

$$K_{p3} = 28.57 \text{ (T-m/deg) for } B_t = 68.8 \text{ tonnes}$$

$$K_{p4} = 35.71 \text{ (T-m/deg) for } B_t = 88.9 \text{ tonnes}$$

The above relationships can be written in a more generalized form (as shown in Figure 3.4):

$$K_{PN} = .211 B_t + 16.80 \quad \text{for } 15.9 \leq B_t \leq 88.9$$

Off-Cushion

$$K_{PF} = 40 \text{ (T-m/deg) for } 15.9 \leq B_t \leq 88.9$$

where K_p = pitch stiffness (N) for on, (F) for off.

B_t = ballast weight (weight of ACIB alone is 166.2 t)

TABLE 3.1

ACIB ALONE PITCH /ROLL TEST DATA TABLE
(Over Water)

TEST #	BALLAST WEIGHT (TONNE)	PITCH MOMENT (TONNE-METRE)	ROLL MOMENT	ON CUSHION*		OFF CUSHION	
				PITCH ANGLE** (DEGREE)	ROLL ANGLE (DEGREE)	PITCH ANGLE (DEGREE)	ROLL ANGLE (DEGREE)
#1	15.90	85.41	1.49	-1.75	2.96	1.80	0.00
#2	15.90	85.17	53.85	-1.50	2.49	0.26	0.43
#3	15.90	84.94	106.22	-1.25	2.99	0.87	1.23
4	15.90	24.09	8.42	-4.20	0.00	-0.77	-0.10
5	44.70	87.27	23.28	-1.20	-0.06	1.45	0.00
6	44.70	86.99	77.45	-0.70	2.22	1.30	0.80
7	44.70	84.61	127.67	-0.40	4.61	1.50	1.40
8	44.70	20.00	26.50	-3.25	0.37	-0.31	0.02
9	68.80	59.78	32.90	-1.50	0.21	1.23	0.02
10	68.80	57.31	84.90	-1.40	2.11	1.20	0.72
11	68.80	54.93	135.10	-1.10	4.27	1.20	1.42
12	68.80	1.38	35.48	-3.30	0.75	-0.30	0.70
13	88.90	47.85	32.90	-1.10	0.41	1.26	0.07
14	88.90	45.47	83.10	-1.40	1.95	1.25	0.60
15	88.90	20.50	104.50	-1.20	2.57	0.62	0.86
16	88.90	45.47	83.13	-1.30	3.01	1.40	0.60
17	88.90	25.02	56.41	-1.80	2.22	0.73	0.21
18	88.90	20.95	-0.53	-2.20	-0.03	0.48	-0.55
19	88.90	45.92	-21.87	-1.50	-1.10	1.20	-0.74
20	88.90	-24.07	28.98	-3.25	0.45	-0.53	0.12
21	88.90	47.85	33.21	-1.25	0.05	0.95	-0.12

* DURING TESTS 1 TO 3 ENGINE RPM WAS 1500

FOR TESTS 4 TO 21 RPM WAS 1800

**FOR PITCH:BOW UP(+)

FOR ROLL:PORT UP(+)

FIGURE 3.2

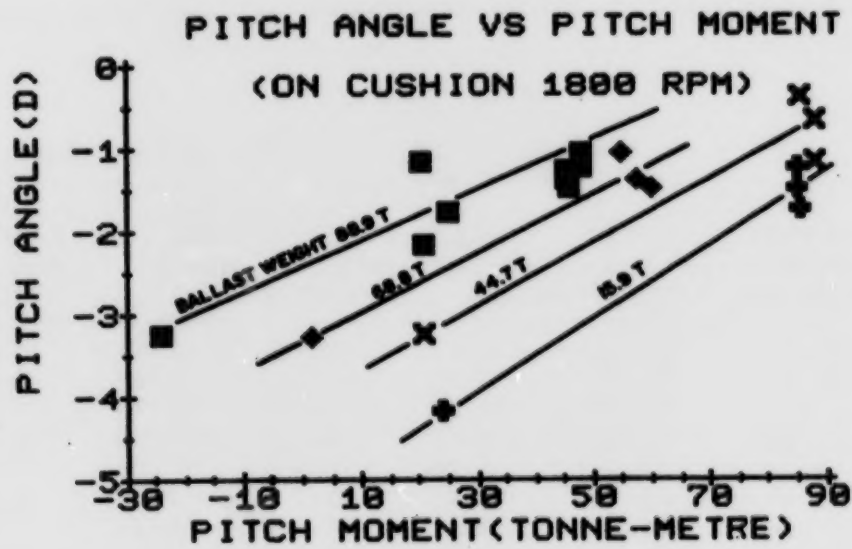


FIGURE 3.3

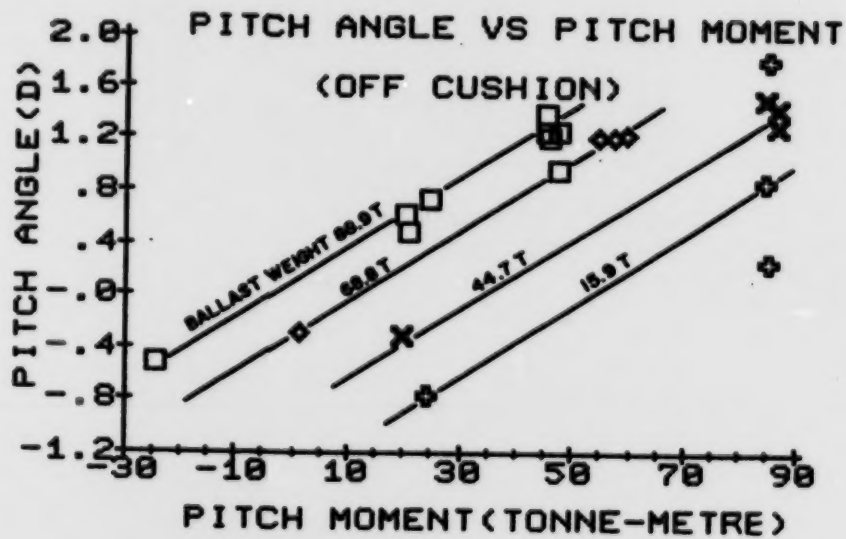
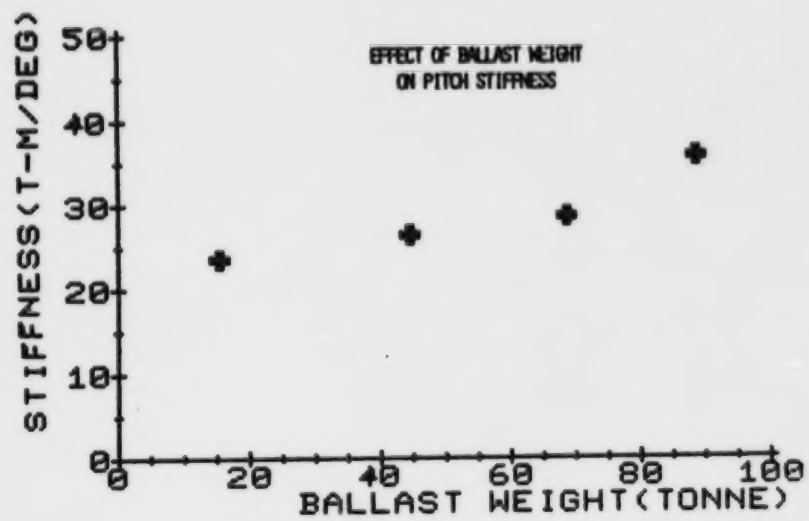


FIGURE 3.4



3.2.2 Roll Stiffness

The roll tests results obtained do not show a similar dependence of the ballast weight on the roll stiffness when 'on-cushion'. The trend of the roll moment versus the roll angle is shown in Figures 3.5 and 3.6. Based on these results the roll stiffness is given by the following relationships:

On-Cushion

$$K_{RN} = 25.64 \text{ (T-m/deg)}$$

Off-Cushion

$$K_{RF} = 76.92 \text{ (T-m/deg)}$$

FIGURE 3.5

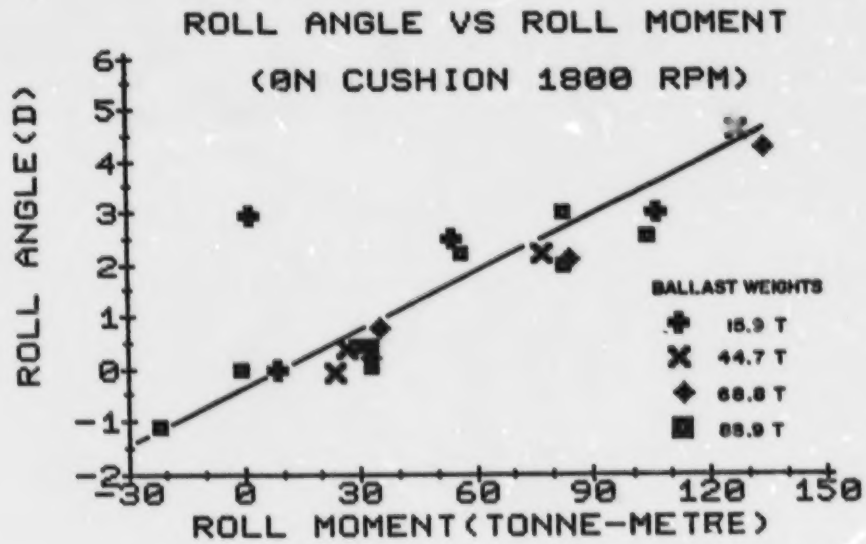
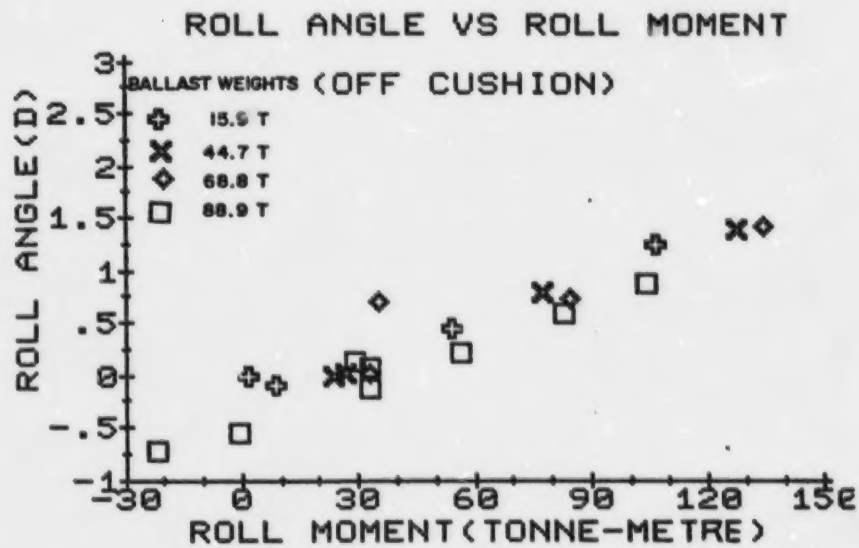


FIGURE 3.6



3.3

ACIB Cushion Pressure

Cushion pressure is one of the most important parameters measured on the ACIB. During these tests the pressure was measured by a water manometer and an electronic pressure gauge mounted at the centre of the craft. The pressure readings are separated into the following four various operating categories: over land, over water, notching over water and over ice. Each category is discussed further in the following subsections.

3.3.1 Over Land

There were no dedicated over land tests. Over land data was recorded during the construction and debugging phases of the ACIB on March 13, 26, 29, 30, and 31, 1982. Much of the data recorded included long periods of constant RPM/pressure operation which is of little interest. Table 3.2 summarizes the useful pressure data collected during this period. No useful data was collected during the third test. The March 13, 1982, data represents the values recorded during the first initial lift-offs at Port Arthur Shipyard (see Figure 3.7). Of most interest here are the pressure oscillations caused by the notch. Due to the lightness of the notch area the fingers fully inflate and lift the aft end to a height where the skirt could no longer provide a good seal. At this time the plenum pressure decreased deflating the skirt to a point where it was able to restore the seal again. With the seal restored the pressure began to increase starting a new cycle. Figure 3.7 represents the worst oscillation encountered which had a frequency of approximately 1 Hz.

3.3.2 Over Water

The over water ACIB cushion pressure data was recorded during the dedicated pitch and roll tests reported in the previous section.

The test consisted of loading the ACIB with ballast weights, then slowly increasing the engines from zero up to 1200, 1500, 1800, and 2000 RPM and simultaneously recording the output of the cushion pressure gauge. One minute was required between each RPM to ensure that the engines had reached a steady condition and to obtain a sufficiently long recorded output. Four different ballast weight conditions were used: 15.9, 44.4, 68.8, and 88.9 tonnes. The results of the tests are summarized in Table 3.3. Figure 3.8 and 3.9 shows the plot of the cushion pressure versus the engines RPM and ballast weights.

FIGURE 3.7

Pressure Oscillations during First Lift Off Trials
On March 13, 1982, (Actual O-Graph Output)

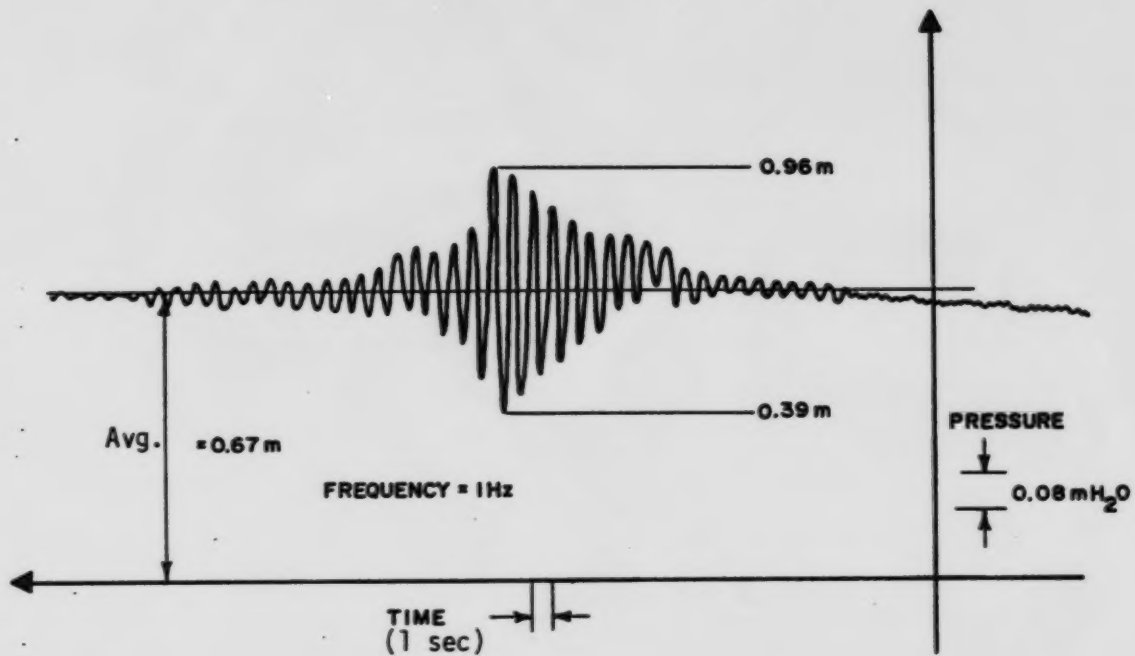


TABLE 3.2

ACIB OVER LAND CUSHION PRESSURE

ENGINES RPM	ACIB WITH NO BALLAST WEIGHT 166 tonnes		ACIB WITH FULL BALLAST WEIGHT 255 tonnes	
	kPa	m H ₂ O	kPa	m H ₂ O
1000	-	-	5.69	.58
1200	4.12	.42	-	-
1500	5.10	.52	7.75	.79
1800	6.57	.67	8.73	.89
2000	6.57	.67	8.73	.89

TABLE 3.3

ACIB OVER WATER CUSHION PRESSURE

ENGINES RPM	BALLAST WEIGHT 15.9 tonnes		BALLAST WEIGHT 44.7 tonnes		BALLAST WEIGHT 63.8 tonnes		BALLAST WEIGHT 88.9 tonnes	
	kPa	m H ₂ O	kPa	m H ₂ O	kPa	m H ₂ O	kPa	m H ₂ O
1200	4.51	0.46	4.51	0.46	4.61	0.47	4.41	0.45
1500	5.98	0.61	6.57	0.67	7.06	0.72	7.06	0.72
1800	5.98	0.61	6.87	0.70	7.26	0.74	7.75	0.79
2000	5.98	0.61	6.87	0.70	7.26	0.74	7.75	0.79

FIGURE 3.8

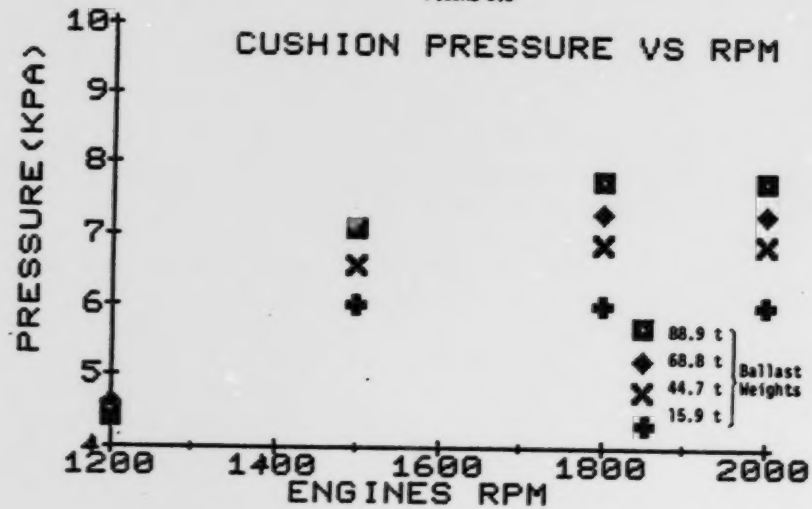
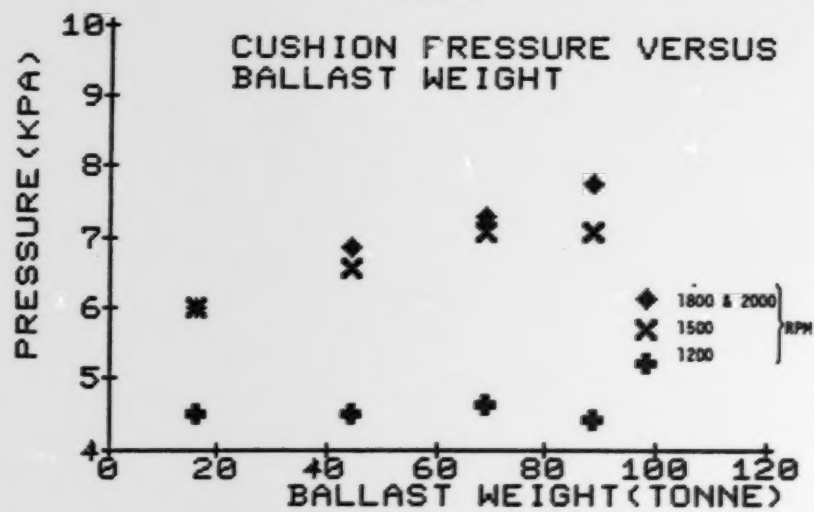


FIGURE 3.9



It can be seen from Figure 3.8 that maximum pressure is reached at 1800 RPM and that no further benefit is incurred by increasing the RPM's. In Figure 3.9 again we see that no benefit is incurred by increasing the RPM beyond 1800. Based on the same figure, there is a linear relationship between the ACIB ballast increase and the cushion pressure increase within the range of ballast added (15.9 to 88.9 tonnes) which can be given for the 1800 engines RPM:

$$\Delta P_c = 2.5 \times 10^{-3} \Delta B_t \text{ for } 15.9 < B_t < 88.9$$

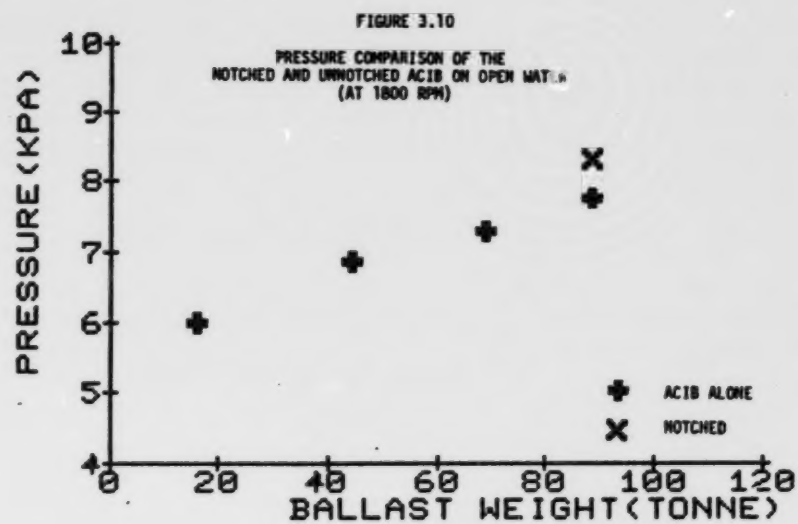
where ΔP_c = increase in cushion pressure (m H₂O)

B_t = Ballast increase in (tonnes)

For ballast weight over 88.9 tonnes, the cushion pressure may either continue to increase or level off, as was observed for the 1500 engine RPM tests as also shown in Figure 3.9.

3.3.3 Over Water (Notched with ALEXANDER HENRY)

The ACIB was first notched into the CCGS ALEXANDER HENRY on April 16, 1982, with 16 tonnes of ballast weights. On April 22, the ACIB was notched with full ballast weight conditions (89 tonnes). The cushion pressure was measured during these two tests and compared to the results obtained with the ACIB alone when tested over water. The result of this comparison is shown in Figure 3.10. The increase of the cushion pressure when the ACIB is notched is mainly due to the reduction of area under the cushion.



3.3.4 Over Ice (Notched with the ALEXANDER HENRY)

The cushion pressure was recorded continuously during the ice tests conducted between April 22 and 29, 1982. The ACIB was therefore notched, at full ballast weight of 88.9 tonnes (total mass 255.1 tonnes) and at 1800 engines RPM conditions.

Figure 3.11 shows a typical air cushion pressure output recorded during a continuous icebreaking run. In general, the pressure fluctuated between 7.7 and 8.3 kPa. An attempt was made to correlate the pressure fluctuations during icebreaking using the video recording of the cushion area. It was found that these fluctuations were mainly due to the broken ice size and concentration under the cushion area. It was noticed that when the ice remained unbroken under the ACIB (during ramming tests) the cushion pressure reached its maximum value of 9.0 kPa (0.92 m of H₂O).

3.3.5 Summary of Cushion Pressure Measurements

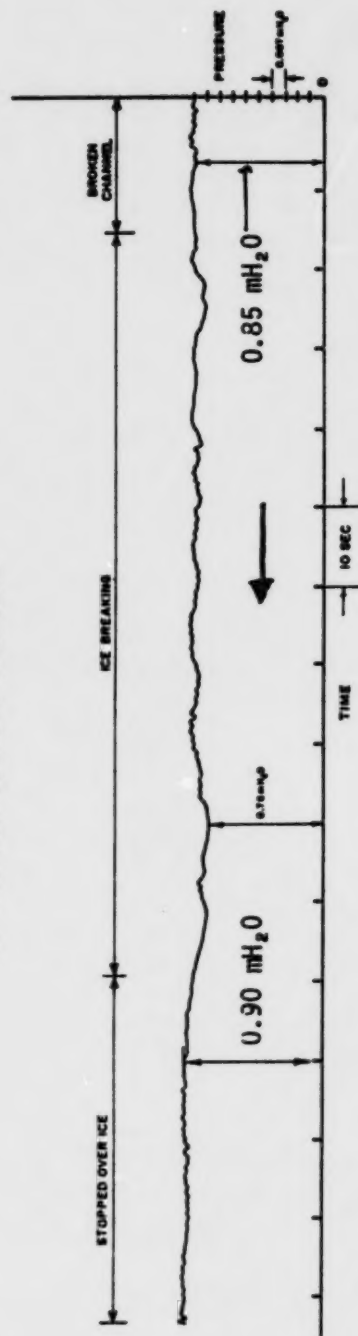
In Table 3.4 cushion pressure values measured during a typical icebreaking run are presented, along with those measured during other tests conducted on the ACIB.

TABLE 3.4

SUMMARY OF THE MEASURED CUSHION PRESSURE VALUES FOR FULL BALLAST CONDITIONS WITH 1800 RPM			
ACTIVITY	CUSHION PRESSURE		COMMENTS
	kPa	m H ₂ O	
Over land	8.3	0.85	ACIB alone
Over water	7.7	0.79	
Over water	8.3	0.85	ACIB with CCGS HENRY
Over broken ice(1)	8.3	0.85	
Over unbroken level ice	9.0	0.92	

(1) 1 HZ oscillation was observed with maximum 0.86 and minimum 0.78 m H₂O cushion pressure.

FIGURE 3.11
TYPICAL O'GRAPH RECORD OUTPUT
OF THE AIR CUSHION PRESSURE



3.4 ACIB Hover Height

The hover height of the ACIB was measured during the hover over water tests conducted on April 14 to 16, 1982. The hover height H , given to the level difference between the bottom of the flotation tank and the water (outside the plenum), was calculated by averaging the deck heights measured at the corners of the ACIB H_d then subtracting the flotation tank depth (Figure 3.12). This height was also compared to a direct measurement made relative to a crane hook kept at a constant height relative to the water level above the center of the ACIB.

The hover height was calculated for each RPM increment (0, 1200, 1500, 1800, and 2000), and each ballast weight increment (0, 15.3, 44.7, 68.8 and 88.9 tonnes). The hover height versus the RPM's of the three engines is presented in Table 3.5 and in Figure 3.13. The hover height versus the ballast weight is also presented in Figure 3.14. On this same figure, the hover height of the ACIB after notching with the ALEXANDER HENRY icebreaker is also shown.

The water level in the cushion area was measured using an electronic water level sounder. The level difference of the water in and out of the cushion area was equivalent to the cushion pressure in m H_2O (as per theories) as long as the RPM is above 1500 and the ACIB flotation tank level is above water.

FIGURE 3.12
SCHEMATIC VIEW OF VALUES

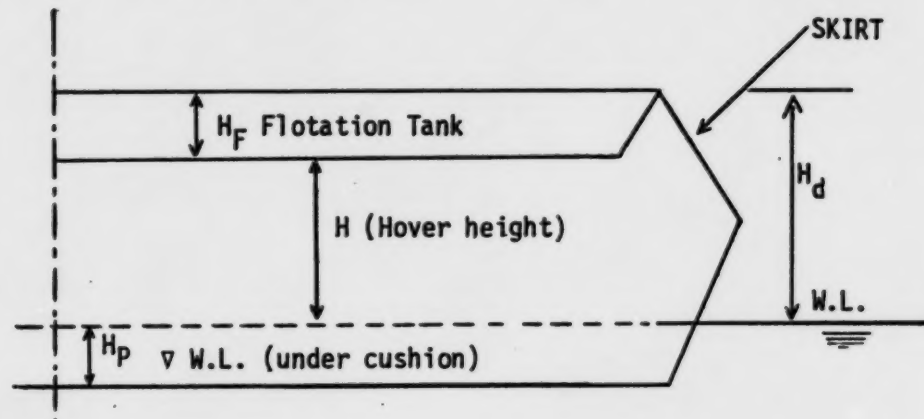
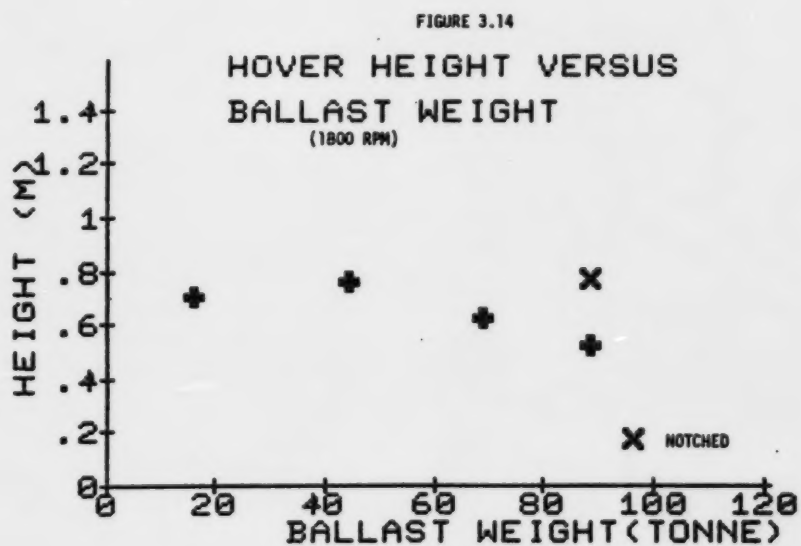
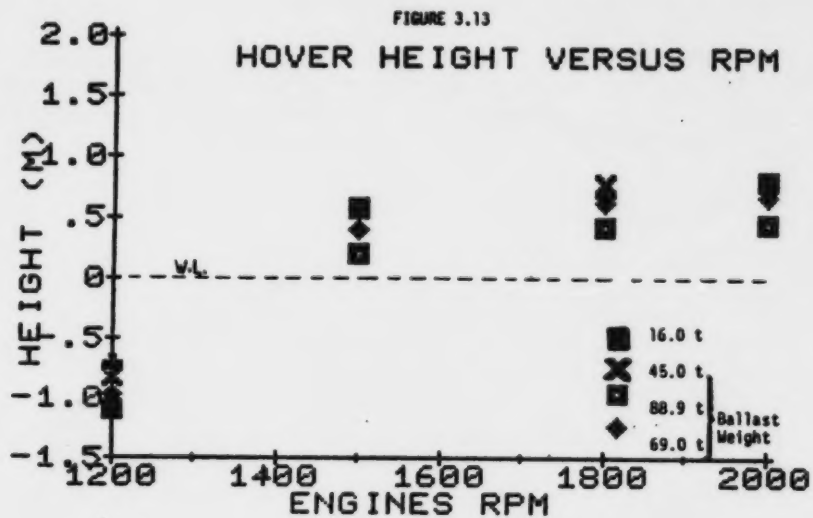


TABLE 3.5
ACIB HOVER HEIGHT (m)

TEST NUMBER	BALLAST WEIGHT (Tonne)	ENGINES (RPM)				
		0	1200	1500	1800	2000
1	15.9	-1.75	-0.65	0.77	0.85	0.88
2		-1.66	-	-	0.91	-
3		-1.63	-0.98	0.24	0.35	-
4		-1.67	-0.56	0.67	0.68	0.70
AVERAGE		-1.68	-0.73	0.56	0.70	0.79
5	44.7	-1.84	-0.86	0.59	0.83	0.85
6		-1.80	-0.82	0.60	0.77	0.80
7		-1.80	-0.79	0.57	0.73	-
8		-1.82	-0.84	0.49	0.70	0.72
AVERAGE		-1.81	-0.83	0.56	0.76	0.79
9	68.8	-1.96	-1.03	0.42	0.71	0.75
10		-1.93	-0.95	0.41	0.65	0.68
11		-1.92	-0.98	0.39	0.57	0.60
12		-1.93	-1.00	0.29	0.54	0.57
AVERAGE		-1.93	-0.99	0.38	0.62	0.65
13	88.9	-2.00	-1.23	0.08	0.55	0.62
14		-2.05	-1.24	0.19	0.54	0.57
15		-2.06	-1.19	0.09	0.55	0.58
16		-2.06	-	-	0.58	-
17		-2.05	-	-	0.51	-
18		-2.07	-	-	0.47	-
19		-1.99	-	-	0.52	-
20		-2.03	-	-	-	-
21		-	-1.11	0.20	0.41	0.43
AVERAGE		-2.04	-1.19	0.04	0.52	0.55
22	88.9	-1.67	-	-	-	-
23		-1.63	-	-	0.40	-
24		-1.65	-	-	0.90	-
25		-1.63	-	-	1.00	-
AVERAGE		-1.64	-	-	0.77	-

Note: 1. ACIB total weight is 166 tonnes.
2. During Test # 22 to 25 ACIB was notched (April 16, 1982).



4. ICEBREAKING SYSTEM CAPABILITIES

The performance evaluation of the air cushion icebreaking bow (ACIB)/ALEXANDER HENRY icebreaking system requires sufficient understanding of both the ACIB and the ship.

Continuous icebreaking cannot be achieved unless the ACIB is capable of breaking the ice and the ship can proceed continuously in the broken channel left behind. In this section the capabilities of the ACIB and the ALEXANDER HENRY are discussed.

4.1 ACIB Capabilities

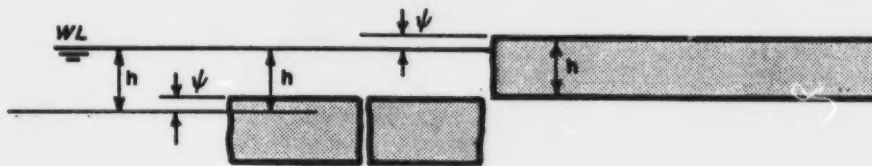
The ice thickness that the ACIB is capable of breaking continuously is limited by the cushion pressure, the ice conditions and the cushion area (shape and geometry). Since the cushion pressure and the cushion area are constants for the present trials, the remaining important factor is the ice condition.

The constant pressure under the ACIB develops a depressed area equal in depth to the cushion pressure in meters of water. This depth should be greater than the total of the following parameters so the air pocket under the ice is maintained (See Figure 4.1):

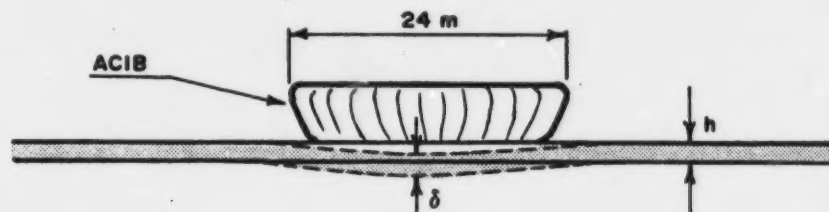
- ° Ice Thickness: The water level in the cushion area should be below the natural water level at a depth equal to the ice thickness. This will insure that the top of the broken ice piece is at the same level as the bottom surface of the unbroken level ice.
- ° Ice Deflection: The ice deflection δ due to part of the weight of the ACIB is important to consider especially when the ice is weak and elastic in late winter. It was estimated that the vertical load applied on the ice is in the order of 75 tonnes. This value was obtained from the ratio of the horizontal pushing force measured by the tension link to the estimated friction factor of 0.1 between the ACIB and the ice.

FIGURE 4.1
REQUIRED CUSHION PRESSURE

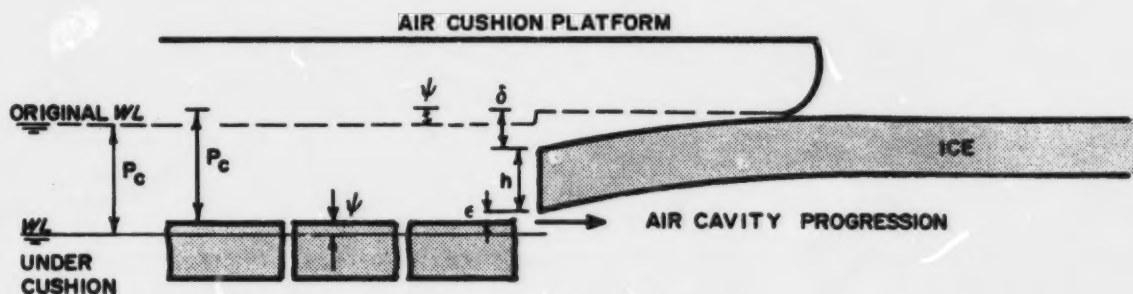
4.1a TO OVERCOME THE ICE THICKNESS (h)



4.1b TO OVERCOME THE ICE DEFLECTION (δ)



4.1c TO PROVIDE A GAP ϵ FOR AIR PROGRESSION UNDER ICE



The deflection was calculated using Wyman's equation for a circular uniformly distributed load over an infinite ice sheet. This assumption is considered to be a good approximation since a more sophisticated math model would not improve the outcome of this analysis. Thus, by neglecting the slot opened by the ship/ACIB system, the deflection in the center of the load can be calculated for the following equation:

$$\delta = \frac{q}{\rho_w g} \left(1 + \frac{a}{l_c} \text{ker}' \frac{a}{l_c} \right) \quad (4.1)$$

where δ = deflection of the ice under the ACIB (m)
 q = distributed load per unit area (Pa)
 $= P/\pi a^2$
 P = Vertical loading (736 kN)
 a = Radius of the Load (radius of ACIB is about 12 m)
 $\rho_w g$ = specific weight of water
 ker' = mathematical function
 l_c = ice sheet characterisic length

$$l_c = \sqrt[4]{\frac{Eh^3}{12 \rho_w g(1-\nu^2)}}$$

E = modulus of elasticity
 h = ice thickness (considered for 0.76 and 0.84 m)
 ν = Poisson ration (0.33)

By solving equation 4.1 for a range of values of the modulus of elasticity, the deflection has been calculated and presented in Figure 4.2 and Table 4.1. This figure shows, that in presence of deterioriated ice ($E=0.1$ to 0.6 GPa) the deflection may increase by two to three folds more than what is expected to be for cold ice.

° Air Gap:

A gap ϵ between the bottom of the unbroken ice and the top of the broken ice should be provided to allow the air under the cushion to progress under the level ice sheet (see Figure 4.1.c). This depth is unknown, however it should not be less than 0.05 m.

In summary, the total cushion pressure in meters of water required by the ACIB to continuously break the ice is given by:

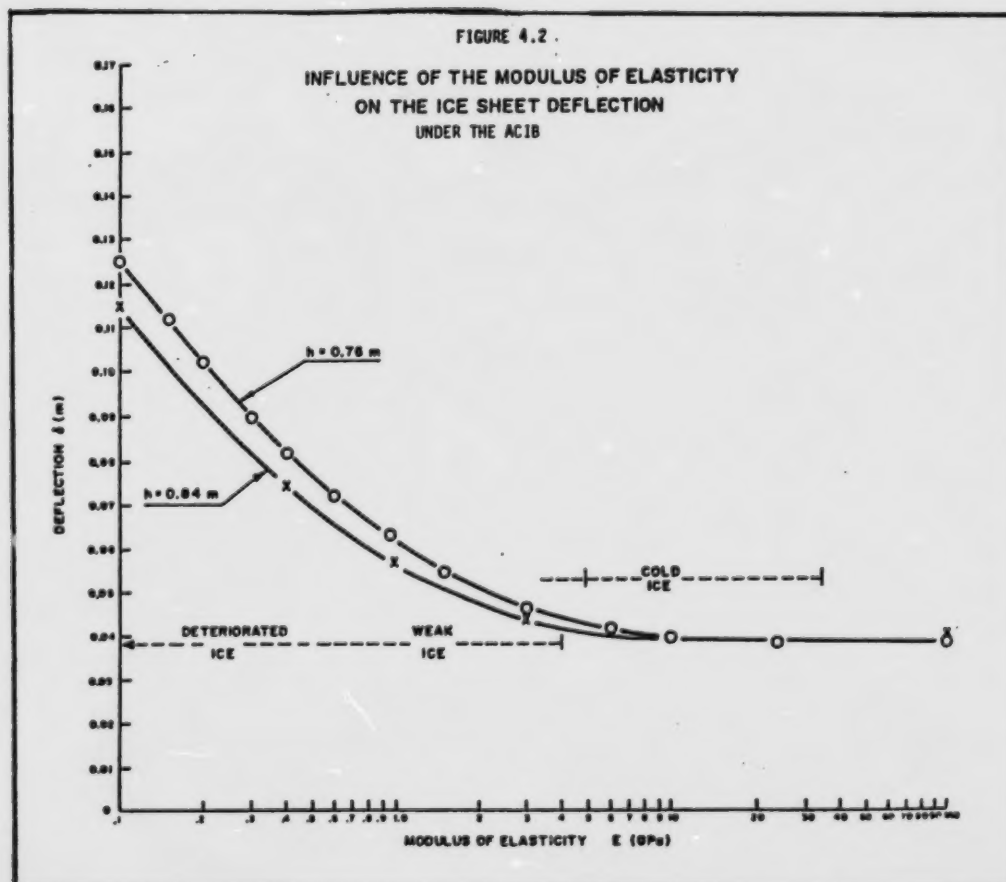
$$P_c = h + \delta + \epsilon$$

TABLE 4.1

INFLUENCE OF THE MODULUS OF ELASTICITY ON THE DEFLECTION OF THE ICE

	h = 0.76 m		h = 0.84 m	
E (GPa)	l_c (m)	δ (m)	l_c (m)	δ (m)
30.0	-	-	20.29	0.0390
25.0	17.98	0.0382	-	-
10.0	14.30	0.0396	15.42	0.0390
3.0	10.59	0.0467	11.41	0.0441
1.5	8.90	0.0549	-	-
1.0	-	-	8.67	0.0565
0.95	7.94	0.0626	-	-
0.40	6.40	0.0821	6.89	0.0745
0.20	5.38	0.1023	-	-
0.15	5.01	0.1117	-	-
0.10	4.52	0.1250	4.88	0.1150

For: $p = 736 \text{ kN}$
 $a = 12 \text{ m}$

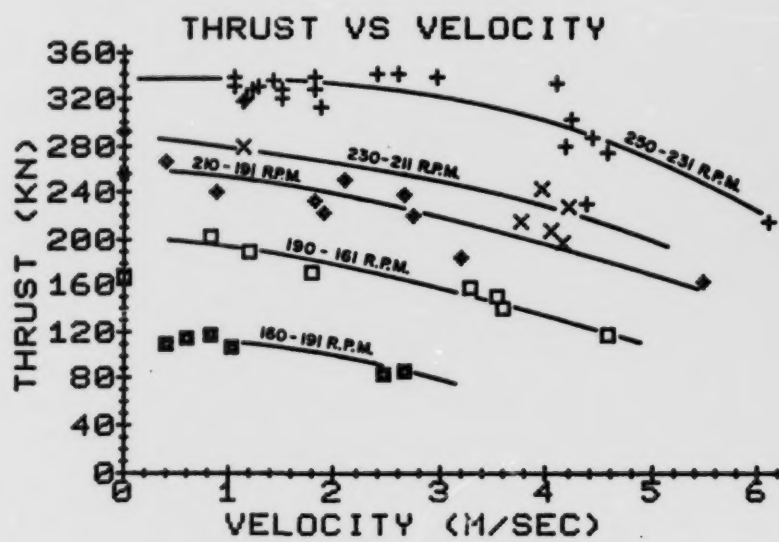


Therefore, considering the actual ACIB pressure of 0.85 m of water the maximum ice thickness expected to be broken in cold winter ice is 0.76 m and in deteriorated ice would be as low as 0.68 m.

4.2 ALEXANDER HENRY Capabilities

The candidate ship should provide the power required to overcome the ACIB resistance over ice, in addition to the resistance due to ice interactions, clearing and friction while moving in the broken channel left behind the ACIB. The ALEXANDER HENRY icebreaker has adequate power to overcome these forces. The ship is capable of thrusting at 330 kN, with maximum RPM and a velocity of 3m/sec ($\approx$ 6 knots) as shown in Figure 4.3. The thrust that the ALEXANDER HENRY actually produced did not exceed 232 kN (Section 5), much below its potential thrust capability. The thrust from that run was determined while pushing the ACIB through .8 m ice thickness.

FIGURE 4.3



5. EVALUATION OF THE ACIB/ALEXANDER HENRY SYSTEMS

5.1 Introduction

Icebreaking tests of the ACIB/ALEXANDER HENRY system were conducted during the period between 22 and 29 of April, 1982. Tests were conducted in Thunder Bay Harbour as shown in figure 5.1.

A total of fifty test runs were made. Approximately ten of these runs were considered to be continuous icebreaking with a penetration length above 60 m (one ship length), however for the remaining runs either the ACIB did not break the ice or the length of the broken ice track was too short. The ice during these tests was very weak and deteriorating. Therefore, before the presentation of the results and the evaluation of the vehicle performance, a brief review of the effect of these ice conditions on icebreaking performance using an air cushion icebreaking bow, must be made.

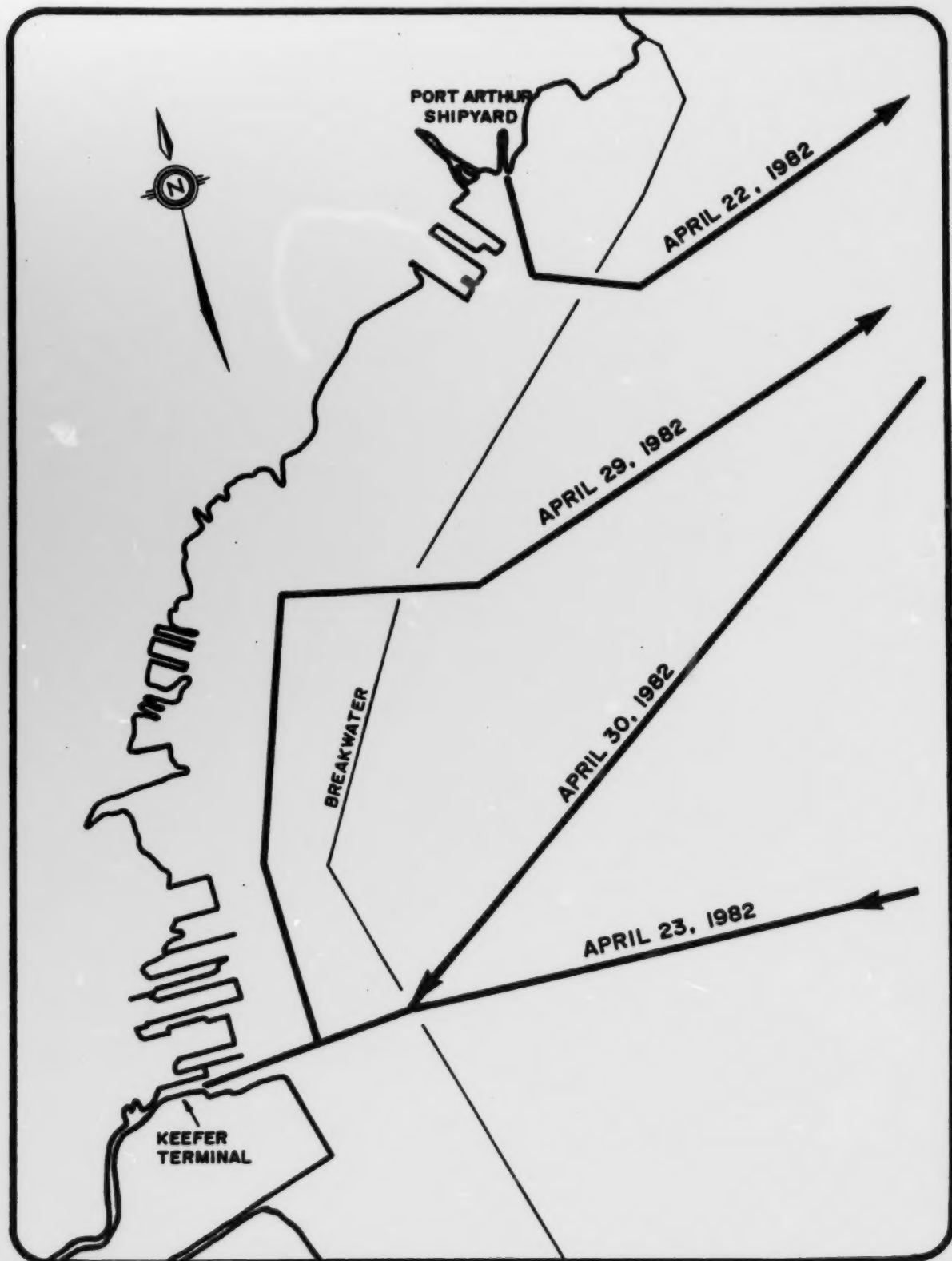
5.2 Ice conditions and Their Effect on Icebreaking

Icebreaking tests were conducted during the end of April 1982. The ice was disintegrating and all the snow on the surface melted forming melt pools which covered 10 to 50% of the ice surface. This ice condition is quite different from the one observed during the tests of the ACT-100/ALEXANDER HENRY system in the winter 1976. In Appendix A, more information about the ice thickness and ice mechanical properties are included.

The primary parameter affecting the ACIB performance is the ice thickness. Based on previous experiments conducted earlier and reported by Wade [9], the cushion pressure in meters of water should be about 1.1 times the ice thickness. In the winter of 1982, the ice thickness measured during testing was between 0.73 and 0.84 m. The ice may have been thicker in early March, but melting was already under way when the present tests were conducted. No attempt was made to cross any rafted ice or other irregularities during the present trials. The average ice flexural strength was 310 KPa (45 psi), which is unusually low when compared to the tests conducted using the ACT-100 with the ALEXANDER HENRY in 1976 and reported by Edwards et al [3].

The modulus of elasticity of the ice decreases more rapidly than its flexural strength, therefore the ice was more elastic than usual. This evidently results in a much higher deflection when compared to a harder ice cover. During the 1977 winter tests with the GRIFFIN and the ACT-100, Dunne [7] reported that during some of the runs, the ice did bend under the ACT-100 rather than breaking. Tests were conducted then in ice weaker than the 1976 tests. A low value modulus of elasticity allows significant deflection before exceeding the failure bending stress of the ice cover.

FIGURE 5.1
TESTING LOCATION IN THUNDER BAY HARBOUR



5.3

Test Results

The results of the tests conducted during the period of 22 to 29 April 1982 are presented in this section. A total of fifty runs were made but continuous icebreaking of more than 60 m penetration was seen only during six runs (See Figure 5.2). The test was interrupted when damage to the bow section skirt occurred. The test results of the six runs are presented in Table 5.1. In Appendix E, the oscillograph outputs are also given. The following are all parameters considered during the test:

- ° Velocity of the Ship/ACIB: The average velocity of the ship was obtained using the doppler radar. The velocity was between 0.23 and 0.56 m/sec (0.45 and 1.1 knots). The ALEXANDER HENRY (alone) cannot maintain a constant velocity in ice this thick, thus no comparable figures are available.
- ° Penetration Distance: The penetration distance of the ALEXANDER HENRY/ACIB system in level ice was calculated by using the duration of each run obtained from the ship bow/ACIB video camera view from above and the average velocity during the run. The duration was between three and eleven minutes, and the penetration distance calculation was between 60 and 220 m. A double check on the penetration distance was made by measuring the distance from the TV monitor screen, then using a reference scale the distance is obtained.
- ° Ice Thickness: The ice thickness and its properties have been discussed in Section 5.1. The thickness was measured usually following completion of a successful run. It was assumed that the ice thickness accurately represented the average ice thickness along the test run.
- ° Ice Mechanical Properties: The ice condition was not adequate to safely support an ice party for measuring the ice properties. In Appendix A, estimate for the ice flexural strength and its elastic modulus was made. Flexural strength was 310 kPa, which corresponds to a modulus of elasticity between 0.3 and 0.6 GPa.
- ° Ship RPM and Thrust: The thrust used by the ship to push the ACIB and move itself through broken ice was about 40 to 70% of the maximum thrust available. The total thrust of the ship during the six runs was between 129 and 232 kN. Most tests were conducted with caution at relatively low RPM's (between 130 and 200 RPM).
- ° Broken Channel Width: The width of the broken channel was on average, equal to the width of the ACIB. The broken ice channel left behind the cushion area was relatively undisturbed. When the ship bow moved in, the center part was displaced by the ship and left behind a track with 8/10 to 9/10 ice concentration. See Plate 5.1 and 5.2.

FIGURE 5.2

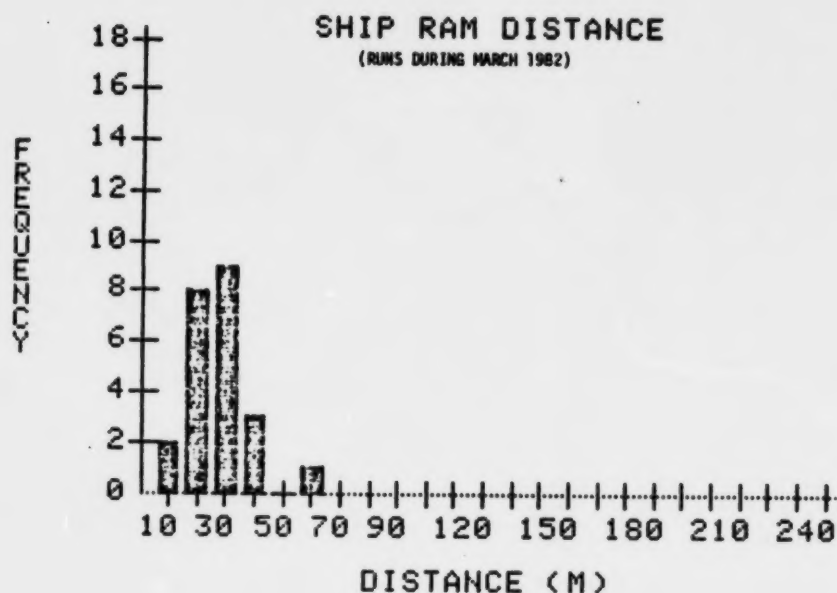


FIGURE 5.3

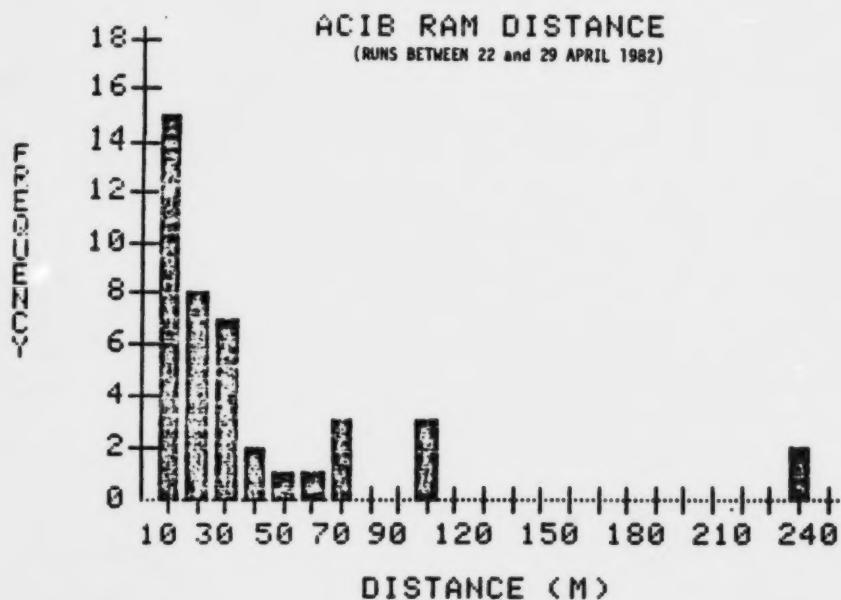


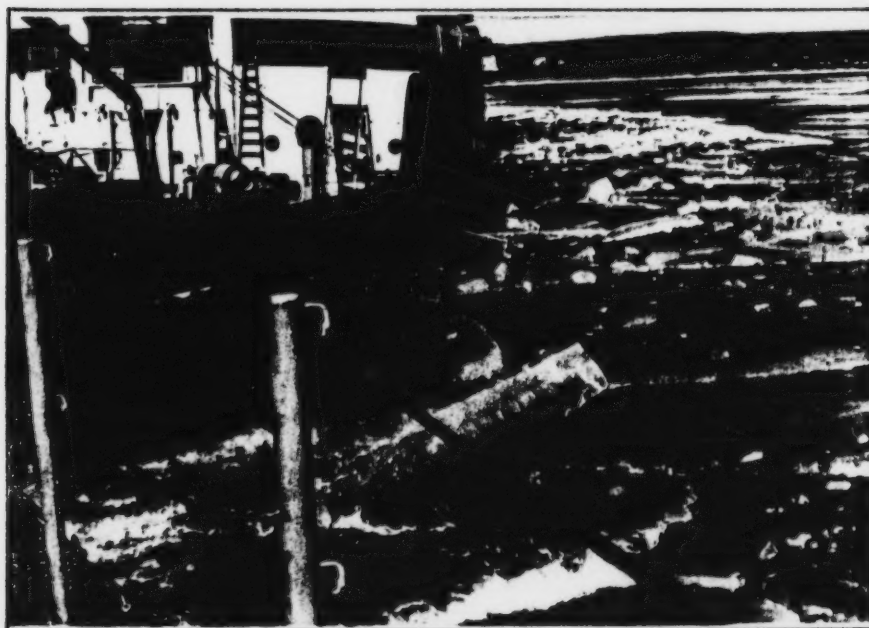
PLATE 5.1

A VIEW FROM THE SHIP



PLATE 5.2

A VIEW FROM THE ACIB



° ACIB Resistance: The resistance of the ACIB over ice was obtained by measuring the force reduction on the tension link between the ALEXANDER HENRY and the ACIB. The tension was measured and was eight tonnes prior to moving the ACIB. The spring factor of contact area (ACIB skirt and ALEXANDER HENRY bow) being much lower than the spring factor of the link cables, the effect of the contact was considered negligible. It should be noted also, that additional cables were used to link the ACIB to the ship. Based on the above, the accuracy of this measurement is somewhat questionable and the values measured are considered to be a minimum value rather than actual value. The average resistance force was between 56 and 76 KN while moving forward and between 23 and 46 KN while moving in reverse.

° Fuel Consumption: There are fuel accumulators on each of the ship's engines. A log of the fuel consumed for different "ship only" operating conditions was made. From this log, a fuel consumption rate of 314 l/hr was measured for "ship only" ramming mode. On the ACIB a similar log was created based on the amount of fuel transferred from ship to ACIB. An estimate of the ship/ACIB fuel consumption during ramming was 400 l/hr.

° Pitch and Roll: The ACIB pitch and roll was measured by liquid damped pendula pots. During icebreaking 1-2 degree pitching and rolling was common. On de-pressurization (coming off cushion) an 8° pitch change was often measured. During the pitch and roll tests, the ship was always stopped; the cushion decay time was not measured; and the consistency and direction were not noted.

° Torque: Strain gauged rosettes were mounted on the shaft to measure rotational strains for torque measurements. The strain signal was amplified and transmitted off the rotating shaft by an FM telemetry system. Torques of 2770 Kg-m was typical.

° ACIB RPM: Due to the static nature of the three engine RPM's, they were most conveniently recorded by voice on the tape recorder and in the tape record book. The engine RPM during the test ran almost exclusively at 1800 RPM.

° Cushion Pressure: The cushion pressure was measured by both an electronic pressure gauge (mounted at the centre of the ACIB) and a water manometer (mounted near the bow of the ACIB). The overwater or broken channel pressure was 0.85 m H₂O and rising as high as 0.92 m H₂O when sitting with a good seal on an unbroken ice sheet.

° The ACIB was designed to produce 6 kPa at 180 tonnes weight. Referring to Table 3.3, 5.98 kPa was measured at 182 tonnes (166.2 + 15.9). At 255 tonnes, the measured pressure was 7.75 kPa. It would appear from Figure 3.9 that at 270 tonnes, the pressure would be 8 kPa. This is lower than the design of 10 kPa at 270 tonnes.

TABLE 5.1
SELECTED RUNS WHERE ACIB BROKE ICE

RUN	DATE	START	END	DURATION (min/sec)	PENETRATION (m)	VELOCITY (m/s)	ICE THICKNESS (m)	THRUST (kn)	SHIP RPM	ACIB RESISTANCE (kn)
1	Apr/22	16:37:39	16:43:03	5:24	180	0.56	0.74	232	194	76
2	Apr/22	16:53:22	16:56:09	2:47	60	0.35	0.75	232	196	74
3	Apr/22	18:30:54	18:34:15	3:21	80	0.40	0.84	223	189	56
4	Apr/23	06:58:00	07:08:21	10:21	140	0.23	0.84	147	149	-
5	Apr/23	07:26:30	07:37:54	11:24	200	0.29	0.84	129	144	-
6	Apr/29	13:34:50	13:41:57	7:07	220	0.52	0.71	-	-	-

Average cushion pressure 8.3 kPa (0.85 m H₂O)
Average flexural strength was 310 kPa

5.4 Comparison with Previous Trials

The results of the present trials were compared to the results obtained during previous trials using the ACT-100 and the CCGS icebreakers during 1976 and 1977 winters. The first field trials conducted in the winter of 1976 used the ACT-100 notched with the CCGS ALEXANDER HENRY (Edwards et al [3]). The second full scale trial during the winter of 1982, was conducted using the ACT-100 while pushed by the CCGS GRIFFON and the CCGS ST CLAIR. Table 5.2 summarizes the results of the previous tests along with the present trial results.

5.4.1 Icebreaking

Icebreaking capabilities of the ACIB and the ACT-100 cannot be compared unless testing in similar conditions are made. The conditions during 1976 tests (ACT-100 with CCGS ALEXANDER HENRY) were significantly different. The ice was weaker due to its continuous disintegration. Using an air cushion vehicle, it is not the strength of the ice that matters but its capability of maintaining a gap under the level ice that allows the propagation of the air. A weaker ice as discussed earlier will deflect more and will not allow the proper functioning of the icebreaking system. During the tests with the ACT-100 (both in 1976 and 1977) the cushion pressure in meters of water was kept equal to the ice thickness.

During these tests, the ice was breaking well during the month of February when the ice was relatively strong (flexural strength was 800 to 500 kPa average) but was difficult to break when the ACT-100 and the GRIFFON was used in March 1977 when the ice was weak (flexural strength was 338 kPa). It is believed based on these experiments that the cushion pressure (in meter of water) should at least be equal to the depth of the ice for ice with a strength above 500 kPa.

TABLE 5.2

COMPARISON WITH PREVIOUS TESTS

TEST	ICE CHARACTERISTIC THICKNESS STRENGTH (M)	ENGINES R P M	THRUST		VELOCITY (M/SEC)	CUSHION PRESSURE		SHIP BEAM (M)	DIMENSIONLESS NUMBERS	
			(TONNE)	(KN)		(KPA)	(H ₂ O)		THRUST (-)	VELOCITY (-)
AH ALONE 1976	0.28	869	29.60	290	0.00	--	--	13.26	28.47	0.00
	0.25	869	20.50	201	0.82	--	--	13.26	24.74	16.65
	0.28	869	32.60	320	1.52	--	--	13.26	31.36	27.56
	0.23	869	23.80	233	1.83	--	--	13.26	33.93	40.40
	0.28	869	24.40	239	0.88	--	--	13.26	23.47	15.96
	0.28	869	33.30	327	1.52	--	--	13.26	32.03	27.56
AH+ACT100 1976	0.56	524	22.70	223	1.89	6.67	0.68	17.37	4.17	14.94
	0.58	524	34.80	341	2.40	6.67	0.68	17.37	5.96	18.36
	0.66	524	34.30	336	2.96	6.67	0.68	17.37	4.53	19.90
	0.64	524	34.80	341	2.60	6.67	0.68	17.37	4.89	18.02
	0.51	490	32.50	319	1.16	6.67	0.68	17.37	7.19	10.09
	0.58	483	34.30	336	1.83	6.97	0.71	17.37	5.87	14.00
	0.71	483	33.30	327	1.83	6.97	0.71	17.37	3.80	11.43
	0.69	483	34.50	338	1.07	6.97	0.71	17.37	4.17	6.88
	0.69	483	34.20	336	1.43	6.97	0.71	17.37	4.14	9.19
	0.71	496	27.20	267	0.40	7.16	0.73	17.37	3.11	2.50
	0.74	496	28.50	280	1.13	7.16	0.73	17.37	3.00	6.77
	0.74	496	33.60	330	1.07	7.16	0.73	17.37	3.53	6.41
	0.76	496	33.60	330	1.28	7.16	0.73	17.37	3.35	7.47
	0.75	828	25.50	250	1.53	7.26	0.74	17.37	2.61	9.05
	0.75	828	34.00	334	3.58	7.26	0.74	17.37	3.48	21.18
	0.75	338	41.70	409	0.83	7.26	0.74	17.37	4.27	4.91
AH+ACT1B 1982	0.74	310	23.60	232	0.56	8.34	0.85	22.60	1.91	2.94
	0.75	305	23.60	232	0.35	8.34	0.85	22.60	1.86	1.81
	0.84	318	22.70	223	0.40	8.34	0.85	22.60	1.42	1.85
	0.84	310	15.00	147	0.23	8.34	0.85	22.60	0.94	1.06
	0.84	310	13.20	129	0.29	8.34	0.85	22.60	0.83	1.34
	0.71	310			0.52	8.34	0.85	22.60		2.85

Ship Length 57.91 m

5.4.2 Thrust

During the previous field trials of the ACT-100 notched to the CCGS ALEXANDER HENRY and the CCGS GRIFFON it was established, as reported by Edwards et al [3] and Dunne [7], that the thrust required to break the same thickness of ice with an air cushion bow was significantly lower than without.

Comparison with Other Icebreaking Tests

The ACIB used during these present tests notched to the CCGS ALEXANDER HENRY showed encouraging results. The thrust of the ALEXANDER HENRY measured while the system was icebreaking was compared to the thrust results obtained during the previous trials. Figure 5.3 shows the thrust versus the icebreaking velocity. The thrust measured when the ACIB was notched to the ALEXANDER HENRY was lower than previous trials with the ACT-100. However, the velocity was not within the same range. In Figure 5.4 an attempt was made to evaluate the effect of ice thickness on the thrust measured, but this attempt failed to show any increase of thrust when breaking thicker ice. This is probably due mainly to the very limited amount of data available.

Comparison with Conventional Icebreakers

Comparison of the thrust measured of the ALEXANDER HENRY with and without an air cushion icebreaking bow cannot be made without using dimensionless relationships. The thrust required by the CCGS ALEXANDER HENRY to continuously break 0.5 meters of ice (minimum ice thickness of which data are available on icebreaking with an air cushion bow) is much above its maximum thrust that can be developed. Thus, ramming will be the prevailing icebreaking mode at that thickness.

FIGURE 5.3

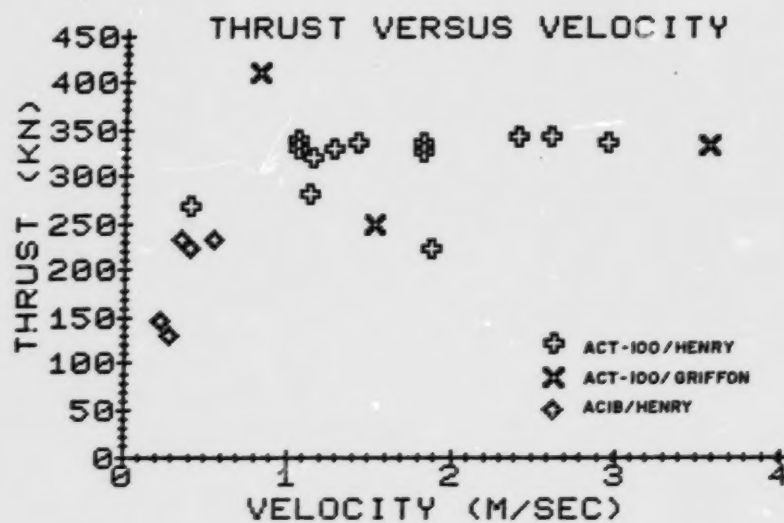
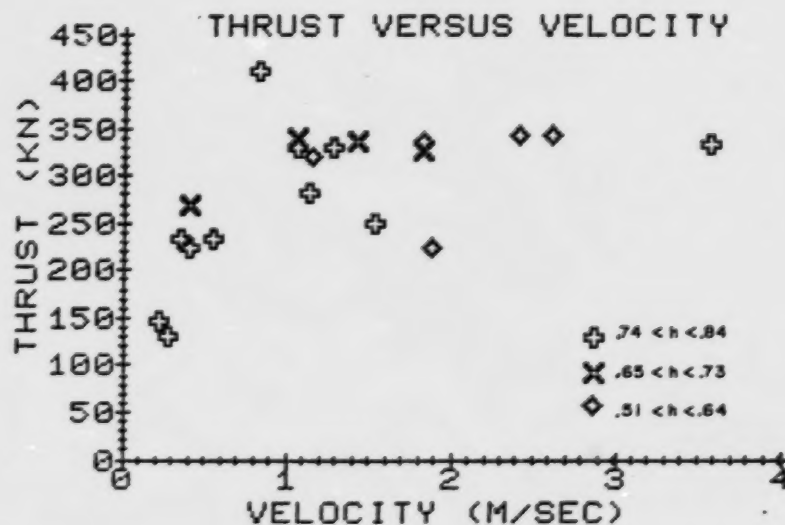


FIGURE 5.4



The dimensionless relationships used for the comparison was given by Lewis et al [15] and are as follows:

$$\text{Dimensionless Resistance} = \frac{R_i}{\rho_w g B h^2} \quad (5.1)$$

$$\text{Dimensionless Velocity} = \left(\frac{V}{\sqrt{gh}} \right) \left(\frac{(L/h)}{\sqrt{B/h}} \right) \quad (5.2)$$

By assuming the pure ice resistance R_i is equal to the thrust (by neglecting the thrust deduction factor), the dimensionless number was calculated for the results of the ALEXANDER HENRY alone tested in 0.3 m of level ice, the ALEXANDER HENRY notched to the ACT-100, the Griffon and the ACT-100 and the present test results. Figure 5.5 shows the substantial dimensionless thrust reduction gained by using an air cushion bow. In Figure 5.6, the regression equations of several conventional icebreakers including an icebreaking cargo ship are plotted together with the data obtained during the present experiments. Based on these results, the performance of the ALEXANDER HENRY/ACIB showed less thrust required than the most efficient conventional icebreaker CCGS PIERRE RADISSON. This does not taken into consideration the power required to keep the platform on cushion.

FIGURE 5.5

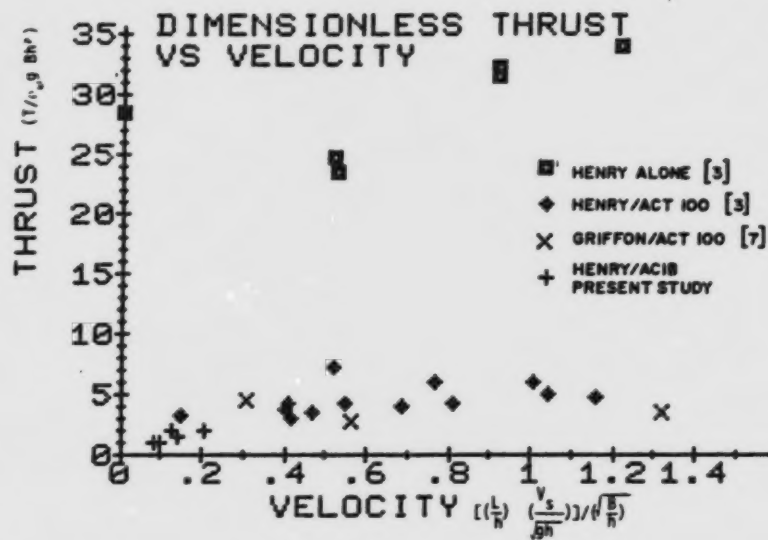
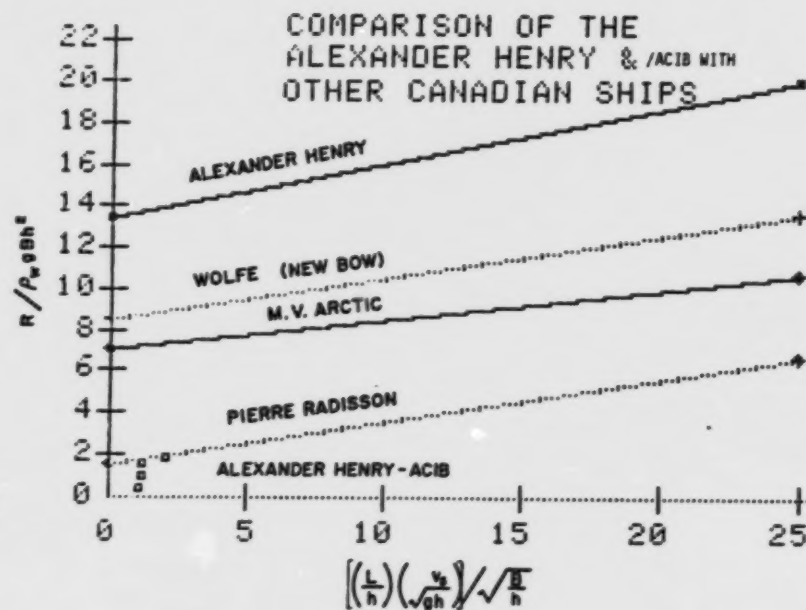


FIGURE 5.6



5.4.3 ACIB Resistance

The resistance force measured on the ACIB was compared to the tow resistance of the ACT-100 in Tuktoyaktuk in 1972. The resistance measured at a velocity of 2.2 m/sec. was below the resistance measured on the ACIB at a velocity of 0.3 to 0.5 m/sec. (the measurement of the resistance of the ACIB as mentioned earlier in the results section is not accurate enough and values are a minimum value). The higher resistance measured is due to a higher cushion pressure required to break thicker ice. In Table 5.3 and Table 5.4 the results of the ACIB and the ACT-100 are summarized. To evaluate the effect of velocity on the ACIB resistance, the results obtained for model tests of a slightly modified ACIB form conducted in 1979 Reference [13] was used. The results are presented in Table 5.5. The resistance versus velocity of the above data are presented in Figure 5.7. Based on these results, the resistance will be expected to increase as observed during the model tests.

FIGURE 5.7

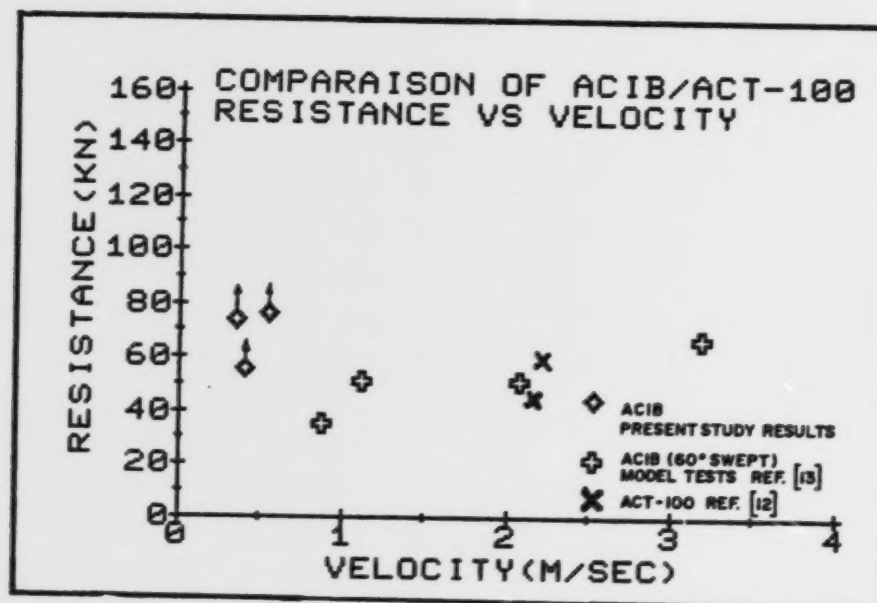


TABLE 5.3

AVERAGE RESISTANCE OF THE ACIB DURING ICEBREAKING

RUN	ICE THICKNESS (M)	VELOCITY (m/sec)	ACIB RESISTANCE (KN)	
			FORWARD	REVERSE
1	0.73	0.56	75.5	
2	0.73	0.35	73.6±12.8	46.1±19.6
3	0.82	0.40	55.9±12.8	22.6± 5.9

Cushion pressure was constant at 8.3 KPa

TABLE 5.4

RESULTS OF THE ACT-100 TOW TESTS TUKTOYAKTUK 1972 [12]

TEST NO.	ICE THICKNESS (M)	VELOCITY (m/sec)	CUSHION PRESSURE (kPa)	AVERAGE RESISTANCE (KN)	
1	0.51	2.1	6.5	49	Breaking Ice
2	0.50	2.2	6.5	58	Smooth Ice

TABLE 5.5

RESULTS OF THE ACIB MODEL SCALE ($\lambda = 12$)
from Abdelnour et al [13]

TEST NO.	ICE THICKNESS		VELOCITY		CUSHION PRESSURE		CUSHION PRESSURE $P_c/\rho_w g h$	AVERAGE RESISTANCE	
	MS (mm)	FS (m)	MS cm/sec	FS cm/sec	MS Pa	FS (kPa)		MS (N)	FS (KN)
1	34	0.41	25.5	0.88	814	9.8	2.4	20.2	34.9
2	34	0.41	32.4	1.12	701	8.4	2.1	29.4	50.8
3	38	0.46	60.4	2.09	733	8.8	2.0	29.4	50.8
4	39	0.47	92.2	3.19	733	8.8	1.9	38.6	66.7

MS is Model Scale and FS is Full Scale.

5.5 Arctic Application

The use of an air cushion icebreaking bow attached or incorporated to the bow of the ship, Ref. [16], is a theoretically feasible alternative to reduce the resistance in level ice. However, the effectiveness of the system when moving through other ice features such as first year ridges, multi-year ridges, broken tracks, rafted ice, etc. is still far from being understood. Therefore, in this section, the discussion will be limited to the system applicability in first year level ice.

Freeze-up in the Arctic starts in early October (Viscount Melville Sound) and reaches an average thickness of two meters by the end of winter. This ice thickness is 2.5 times larger than the average ice thickness measured at the end of the winter in Thunder Bay.

The air cushion icebreaking bow to be considered for the Arctic (2 m ice thickness) will require the modifications of the characteristics of the ACIB for efficiently breaking the ice. The factors influencing the ACIB icebreaking effectiveness are given by the following:

$$\text{Icebreaking} = f(L, B, P_c, H, R_A, \dots)$$

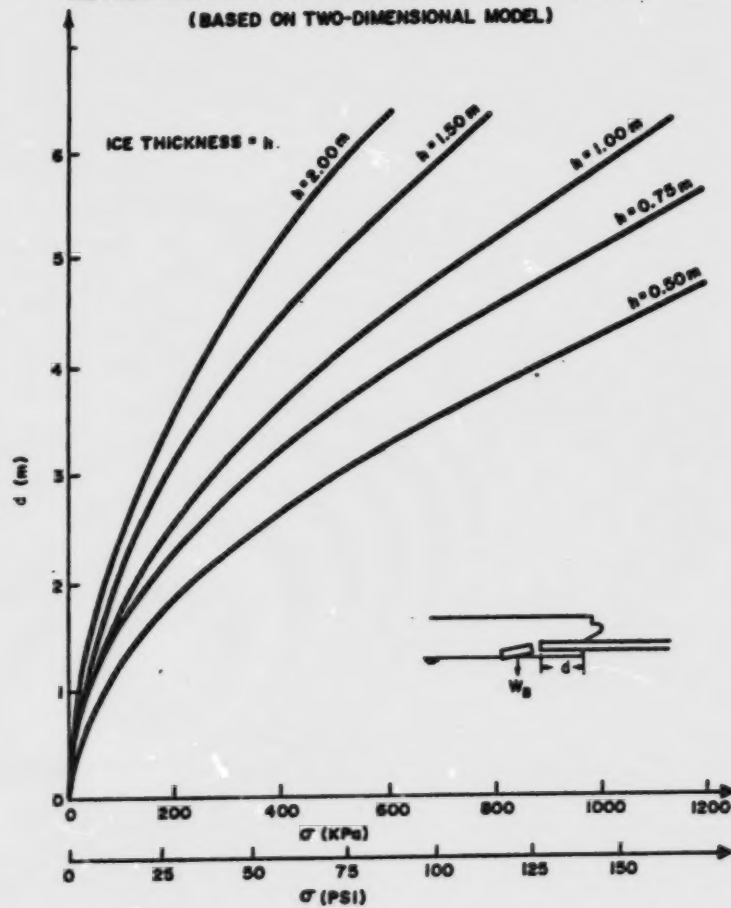
The arctic ACIB preliminary requirement is calculated by considering the present ACIB design characteristics, and assuming that it will be capable to break the winter ice with the same or better efficiency than the ACT-100.

- ° ACIB LENGTH (L): The length of the cushion from the leading edge of the forward skirt to the apex of the notch is an important factor to consider. If the ship is not to contact intact ice, thereby greatly increasing resistance, this length must be greater than the cantilever length of the ice when it fails under its own weight. This length can readily be estimated from the expression below (See Figure 5.8).

$$d = \sqrt{\frac{\sigma h}{3\rho_w g}}$$

FIGURE 5.8

ICE FLEXURAL STRENGTH VERSUS PIECE SIZES OF THE BROKEN CUSPS
(BASED ON TWO-DIMENSIONAL MODEL)



° ACIB beam (B): The width of the ACIB is related to the ice characteristic length. The beam should be wide enough to allow the ice to break and generate cracks in the longitudinal direction. The characteristic length is given by:

$$l_c = \sqrt[4]{\frac{Eh^3}{12\rho_w g (1-\nu^2)}}$$

Therefore, the required increase of the ACIB width for Arctic 2 m ice by assuming the modulus of elasticity is constant is:

$$\lambda_B = \frac{B_1}{B_2} \frac{l_{c1}}{l_{c2}} = \frac{\sqrt[4]{h_1^3}}{\sqrt[4]{h_2^3}} = 2.0 = \sqrt[4]{\frac{h_1^3}{h_2^3}}$$

Therefore, the beam should be wider by a factor of two for 2 m level ice thickness.

° Cushion Pressure (P_C): The cushion pressure in meters of water, should be about 0 to 10% higher than the ice thickness to allow the propagation of the air cavity under the penetrating ice cover. The scaling factor is given by:

$$\lambda_h = \lambda_p = \frac{P_{c1}}{P_{c2}} = \frac{h_1}{h_2} = 2.5 = \lambda_p$$

The cushion pressure measured during the present trials was 8.3 kPa, therefore, the cushion pressure required for an Arctic ACIB is 21 kPa.

° Pushing Force (R_A): The resistance (or thrust) measured during the present experiments was less than measured during the experiments with the ACT-100, however the velocity was of a lower range as well. Based on previous and present tests, effect of the ice thickness on the resistance was not clear. It is obvious however, that resistance must be higher when the icebreaker behind the ACIB has to clear much larger ice masses.

6. CONCLUSIONS

The tests conducted to determine the basic operating characteristics of the ACIB were completed successfully. The evaluation of the icebreaking performance of the ACIB/CCGS ALEXANDER HENRY was also made but due to the limited amount of data collected and limited ice conditions tested, a comprehensive evaluation was not possible.

6.1 ACIB Operating Characteristics

The objectives set to achieve during this study as regards to the ACIB operating characteristics were met. The following are the conclusions.

- ° The measured total weight of the ACIB was 166.2 tonnes. The total weight of the ballast used was 88.9 tonnes.
- ° The ACIB pitch and roll stiffness "on" and "off" cushion were measured. The pitch stiffness on cushion showed some increase when the ballast weight increases from 23.3 T-m/deg with 15 tonnes ballast to 35.7 T-m/deg with maximum ballast of 89 tonnes. The "on" cushion roll stiffness was unaffected by the ballast weight and was 25.6 T-m/deg. The "off" cushion pitch stiffness was 40 T-m/deg and roll stiffness was 76.9 T-m/deg.
- ° The maximum cushion pressure achieved with the ACIB over water and broken ice was 7.75 kPa (with maximum ballast weight and at 1800 RPM). Highest cushion pressure was measured over level ice (during ramming) and was 9.0 kPa.
- ° The hover height of the ACIB while hovering over water was 0.52 m (with maximum ballast weight and at 1800 RPM). When the ACIB was notched to the ALEXANDER HENRY, the hover height increased to 0.77 m.

6.2 ACIB/ALEXANDER HENRY Icebreaking Trials

The original plan set in early January was partly met due to several problems encountered during the ACIB operating characteristic tests. The test started the 21st of April while the ice was deteriorating and ended almost a week later due to a major tear of the skirt in the bow section. Therefore the results available are collected in one ice condition. The following are the conclusions made, based on the limited data base available:

- ° Fifty runs were conducted in which six runs showed successful icebreaking. When the ACIB moved across, excessive bending of the ice occurred. This bending prevented the air cavity from forming under the ice, which prevented the ice from breaking. A similar problem was encountered during the 1977 trials with the ACT-100/CCGS GRIFFON where the ice was difficult to break due to excessive bending. Noting that, with the same system, a month earlier (when the ice was harder) icebreaking was possible.
- ° The maximum thrust required during the six successful runs was 232 KN. That is 70% of the maximum thrust of the ALEXANDER HENRY. The thrust measured during this present study was less than previously measured with the ACT-100/ALEXANDER HENRY in 1976, but so was the velocity.
- ° Use of the ACIB with the CCGS ALEXANDER HENRY greatly improved its capability to break ice. Through dimensionless relationships, the comparison of the ACIB/ALEXANDER HENRY system with the "PIERRE RADISSON" and other icebreaking ships was possible. The ALEXANDER HENRY/ACIB system showed the lowest thrust requirement to go through the same ice condition and was about 50% better than the best Canadian icebreaker, the "PIERRE RADISSON".
- ° The torque and thrust measured on the propellers during icebreaking with the ACIB was as in open water. No ice milling was observed due mainly to testing at very low speed.

7. RECOMMENDATIONS

The following are recommendations to be considered for future trials:

- ° Ice Conditions: The test program conducted in the winter 1982 using the ACIB/ALEXANDER HENRY system was essentially in one ice condition. Tests in at least two different ice conditions are desirable. Ice mechanical property tests including flexural strength and elastic modulus should be made to properly evaluate their effects.

- ° Ice Thickness: Tests in two and preferably three ice thicknesses will help determine the thickness effect on the ship thrust and cushion pressure required to break the ice in various conditions. These measurements will be required should a larger version and more capable icebreaking ACIB/ship system be designed for use in the Arctic.

- ° System Velocity: The average velocity of the ACIB/ALEXANDER HENRY during the present field trials was below 0.5 m/sec. This velocity is well below the design velocity of the ACIB. Future tests should consider a velocity range between 0.5 and 4.5 m/sec. The torque and thrust on the propulsion system should be carefully monitored to avoid overstressing the propeller blades during ice milling. The velocity effect determination will help design a more capable ACIB in future.

- ° Higher Cushion Pressure: The maximum cushion pressure of 8.3 kPa can be increased by adding more ballast weight. With the present maximum ballast, the hover height of the ACIB is 0.77 m (Figure 3.12). Unfortunately, there is no available data to predict the hover height resulting from additional ballast weights.

- ° Continuing the development of mathematical models to predict and design more efficient air cushion icebreaking bows.

- ° Conduct model scale experiments using urea doped ice where correct scaling of the ice properties are possible. Model tests will be used as well to investigate the effect of various ice features on the icebreaking capability of an air cushion icebreaking bow.

8. REFERENCES

- [1] G. Comfort, J. Dubois and M. Steele, "Proposed Test Plan for Trials of ACIB at Thunder Bay", Transport Canada, ARCTEC CANADA Report 1101P, November 1981.
- [2] V. Bulat and H. Blount, "Winter Trials of CCGS Alexander Henry", Transport Canada, ARCTEC CANADA Report 582B, September 1980.
- [3] R.Y. Edwards, J.P. Nadreau and M.A. Dunne, "Results of Full Scale Field Trials of ACT-100 with CCGS Alexander Henry", Transport Canada, ARCTEC CANADA Report 150C, October 1976. T.P.# 862.
- [4] M. Hetenyi, "Beams on Elastic Foundation", The University of Michigan Press, 1946.
- [5] M. Wyman, "Deflection of an Infinite Plate", Canadian Journal of Research, A, 28, pp. 293-302.
- [6] R. Frederking and F.V. Hansler, "The Flexural Behaviour of Ice from Insitu Cantilever Beam Tests", International Association of Hydraulic Research on Ice Problems, Lulea, 1978.
- [7] M. Dunne, "Results of Tests Conducted Using Ships of Two Different Breadths to Push an Air Cushion Transporter in Ice", Transport Canada Research and Development Agency, ARCTEC CANADA LIMITED report 207C-2, June 1977. T.P. #1266.
- [8] T. Kotras, J. Lewis and R. Etzel, "Hydraulic Modelling of Ice Covered Waters", POAC 79, St. John, Newfoundland, 1979.
- [9] Wade, R.G., Edward, R.Y. and Kim, J.K., "Improvements in Ice Breaking by Use of Air Cushion Technology" Society of Naval Architects and Marine Engineers, Ice Tech Symposium, Montreal, Canada, April 1975.
- [10] M.A. Ball, "Air Cushion Ice Breaking - What is the Potential", Eleventh Canadian Symposium on Air Cushion Technology, Vancouver, September 1977.
- [11] Abdelnour, R., and Sayed, M. "Technological Alternatives to the Use of the CCGS Icebreakers at Thunder Bay Harbour", Transport Canada, ARCTEC CANADA report 1115C, July 1982.
- [12] Personal communication with Mr. R. Wade of the Ministry of Transport, Air Cushion Vehicle Division.
- [13] Abdelnour, R., Noble, P., and Hope, A., "Model Tests of Air Cushion Icebreakers". Presented at the 13th Canadian Symposium on Air Cushion Technology, Montreal, September 1979.
- [14] Kashtelyan et al, "Resistance of Ice to Motion of Ships", Sudstroenie, Leningrad, 1969.

[15] Lewis, J., DeBord, F., and Bulat, V., "Resistance and Propulsion of Ice-Worthy Ships", Submitted to the Society of Naval Architects and Marine Engineers, November 1982.

[16] Laframboise, J.E. "Comparative analysis of Icebreaking: Conventional versus Air-Cushion", presented at the 13th Canadian Symposium on Air Cushion Technology, Montreal, September 1979.

[17] Abramowitz, M., and Stegun, I.A., "Handbook of Mathematical Functions", National Bureau of Standards, 1964.

APPENDICES

A.1 Ice Thickness and Properties Measurements

Due to safety reasons, the ice thickness and properties were not measured as was originally proposed. The ice was very weak and disintegrated in some areas, thus the ice party was not allowed to perform (as done in earlier tests) cantilever beams for estimating the strength and drilling holes through the ice for measuring the thickness. However attempts have been made to obtain with less accuracy the ice physical and mechanical properties.

A.1.1 Ice Thickness

The actual ice thickness was measured during the trials. The ice thickness during the ACIB/Henry Tests was 0.73 and 0.84 m (28.7 and 33.1 inches). This data was collected at one location for each successful run. This thickness compares well with the predicted average ice thickness Table at that time of the year for Thunder Bay Harbour as shown in Figure A.1. This thickness prediction is based on average temperature records collected during the last three decades and calculated using Stefan's formula:

$$h = 0.034 \alpha \sqrt{D}$$

where h = ice thickness (m)
 α = coefficient (0.6 for Thunder Bay)
 D = cumulative freezing degree days (1450 for an average winter in Thunder Bay Harbour)

Based on direct measurement of the ice in the harbour, the average maximum ice thickness obtained from data gathered between 1957 to 1981 and presented in Table A.1 is 0.78 + 0.14m (31 in.).

The record for the period between 1957 and 1974 was obtained from the Atmospheric Environment Service, Fisheries and Environment Canada, Report CLI-1-77. Records between 1975 and 1981 were obtained from correspondence with Ice Climatology and Applications, Environment Canada. All reported values are averages of the maximum ice thickness inside the harbour. Other measurements, obtained by ARCTEC CANADA LIMITED are shown in Table A.2 and are in good agreement with the above data.

APPENDIX A.0

MEASURED ICE THICKNESS

DATE	NUMBER OF TESTS	HOUR	ICE THICKNESS	
			(m)	(in.)
April 22	23	12:00 am	0.72	28.5
		4:30 pm	0.74	29.0
		5:30 pm	0.76	30.0
		6:15 pm	0.89	35.0
		6:30 pm	0.84	33.0
April 23	18	4:00 am	0.82	32.0
		6:00 am	0.84	33.0
April 29	10	11:00 am	0.61	24.0
		1:25 pm	0.71	28.0
		1:40 pm	0.71	28.0

FIGURE A.1

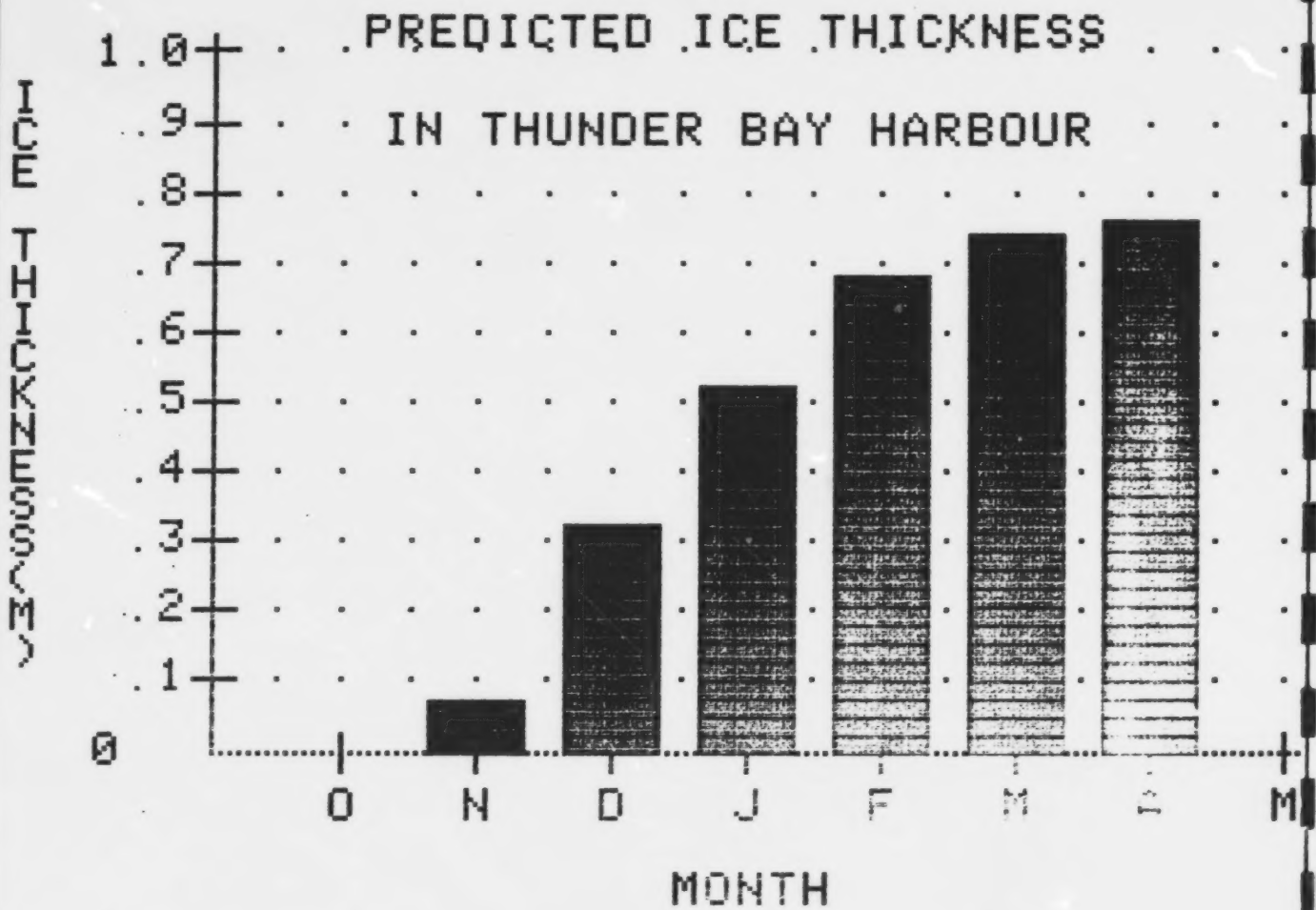


TABLE A.1
MEASURED ICE THICKNESS
FOR THE LAKEHEAD HARBOUR FOR THE PERIOD
BETWEEN 1957-1982

YEAR	MAXIMUM ICE THICKNESS	
	(M)	(IN)
1957	.64	25.20
1958	1.12	44.09
1959	.91	35.83
1960	.91	35.83
1961	.76	29.92
1962	.86	33.86
1963	.61	24.02
1967	.99	38.98
1968	.69	27.17
1969	.61	24.02
1971	.96	37.80
1972	.61	24.02
1974	.62	24.41
1975	.67	26.38
1976	.79	31.10
1977	.84	33.07
1978	.81	31.89
1979	.81	31.89
1980	.71	27.95
1981	.74	29.13
AVERAGES	.78	30.83

TABLE A.2
ICE THICKNESS FOR LAKEHEAD HARBOUR
(ARCTEC CANADA DATA)

YEAR	ICE THICKNESS		DATE
	(m)	(in)	
1976	0.76	29.9	23 March
1977	0.84	33.1	19 February
1980	0.74	29.2	15 March
1982*	0.84	33.0	22 April

*Ice Melting was in progress, estimated maximum thickness is about 1 m.

FIG. A. 2

ICE FLEXURAL STRENGTH VERSUS PIECE SIZES OF THE BROKEN CUSPS
(BASED ON TWO-DIMENSIONAL MODEL)

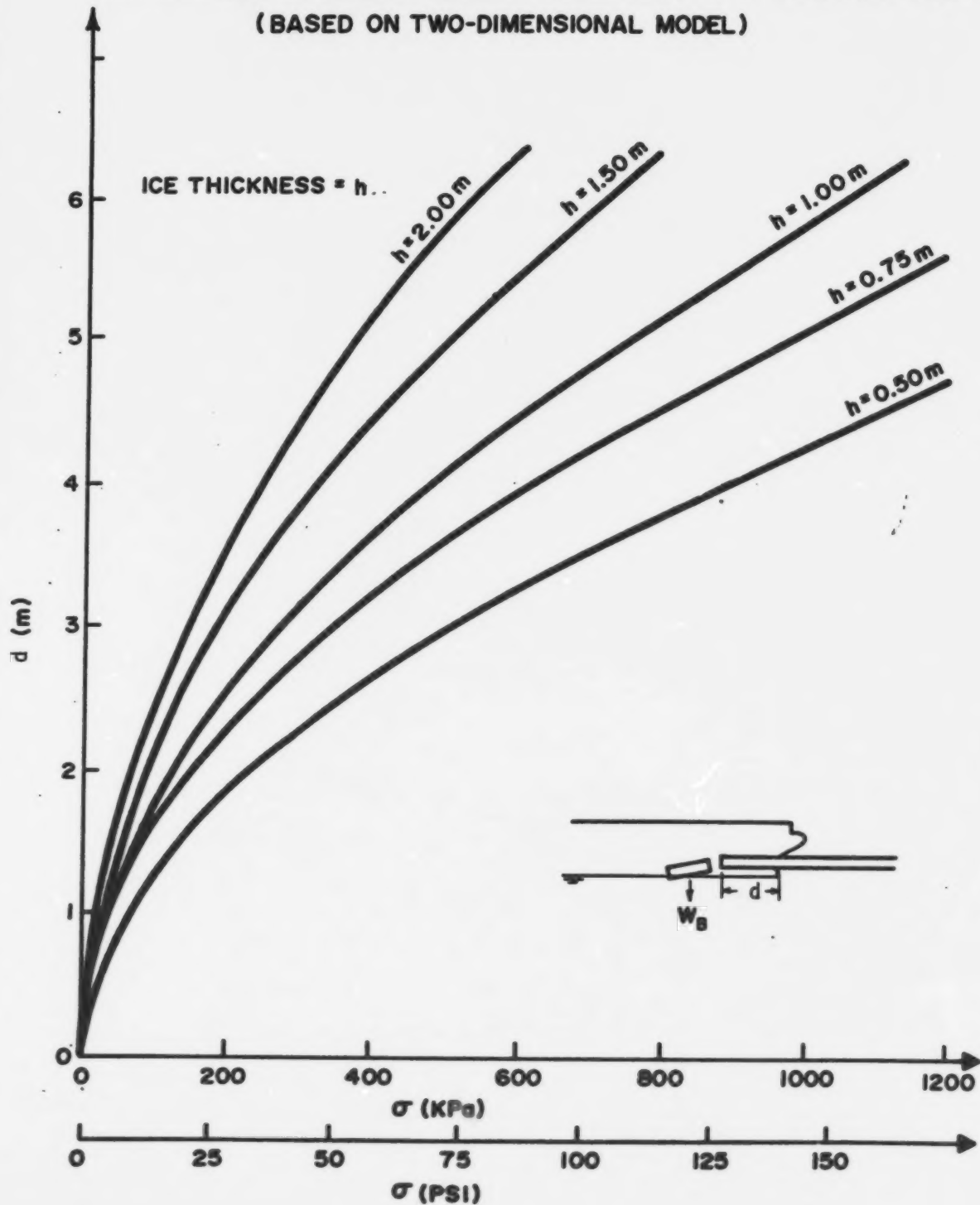


TABLE A.3

RUN# 2			
TIME BETWEEN FAILURES	LENGTH OF BROKE PIECES	ESTIMATE OF FLEXURAL STRENGTH	
(SEC)	(M)	(KPA)	(PSI)
7.00	2.45	232	33.60
9.90	3.47	464	67.20
6.90	2.42	225	32.65
7.30	2.56	252	36.54
9.40	3.29	418	60.59
9.70	3.40	445	64.52
9.80	3.43	454	65.85
3.40	1.19	55	7.93
6.50	2.28	200	28.97
7.77	2.72	305	44.20

RUN# 3			
TIME BETWEEN FAILURES	LENGTH OF BROKE PIECES	ESTIMATE OF FLEXURAL STRENGTH	
(SEC)	(M)	(KPA)	(PSI)
7.90	2.80	303	43.88
5.50	1.90	139	20.21
14.10	4.90	927	134.39
4.50	1.60	99	14.33
7.90	2.80	303	43.88
5.40	1.90	139	20.21
7.55	2.65	318	46.15

A.1.3 The modulus of elasticity of the ice

To our knowledge there is no data available on the modulus of elasticity of fresh water ice measured by using cantilever beams in which temperature of the ice was varied.

Therefore, extrapolation from sea ice should be made in regard to effect of flexural strength and the temperature of the ice on the modulus of elasticity. A full scale cantilever tests on sea ice has been made to measure E and σ . The average thickness of the ice was 0.43 m. As shown in Table A.4, the flexural strength measured averaged 340 kPa and the modulus of the ice average was 2030 mPa. The ratio of the modulus to the strength value is $E/\sigma = 5843$. This ratio based on our experience is between 1000 and 20,000 for sea ice and about similar for fresh water ice and depends as well on the flexural strength of the ice as suggested by Kotras et al [8].

Therefore, based on the flexural strength measured during the 1982 winter trials and compared to previous years, the value of σ is significantly lower than average. Flexural strength measured was between 300 and 1200 kPa. This year the strength was 310 kPa (average value). Thus, E/σ is in the low range as well. Therefore by considering $E/\sigma = 1000$ to 2000, the value of E would be between 0.3 and 0.6 GPa (45,000 and 90,000 psi).

The value of the modulus of elasticity in normal winter period is however much higher. The value of the flexural strength is about 900 kPa for fresh water ice and E/σ ratio is about 10 to 20,000. Therefore the value of E would be between 8 and 18 GPa.

TABLE A.4
RESULTS OF INSITU CANTILEVER BEAM TEST
ISFJORDEN, SPITSBERGEN APRIL 77
[After 6]

TEST NO.	BEAM LENGTH L (M)	BEAM WIDTH B (M)	ICE THICKNESS H (M)	RATIO L/H (-)	MODULUS OF ELASTICITY E		FLEXURAL STRENGTH SIG		RATIO E/SIG (-)
					(GPA)	(PSI)	(MPA)	(PSI)	
1	3.80	0.67	0.44	9	2.30	333333	0.35	51	6571
2	3.96	0.64	0.42	9	2.08	301449	0.33	48	6303
3	3.98	0.60	0.43	9	3.17	459420	0.46	67	6891
4	4.01	0.78	0.44	9	1.30	188406	0.32	46	4063
5	3.95	0.72	0.45	9	1.90	275362	0.35	51	5429
8	3.57	0.61	0.38	9	1.45	210145	0.25	36	5800
AVERAGE	3.88	0.67	0.43	9	2.03	294686	0.34	50	5843



APPENDIX B

INSTRUMENTATION

This table lists all of the measured variables and indicates their operational status during the tests. Every parameter with non-op status is briefly discussed in a paragraph following the table.

TABLE B1

PARAMETER	<u>ACIB</u> METHOD	STATUS
Pitch	Pendula Pots	Operational
Roll	Pendula Pots	Operational
Cushion Pressure	Semiconductor Strain Gauge pressure sensor. Manometers	90% Operational, had problems last day. Operational (Supplied by TDC)
Rise Height	3 Sonic Transducers	Non-Op
Engine/rpm Speed	Manually logged	Operational
Fuel Consumption	Manually logged	Operational
Fan Air Flow	—	Deleted
Surge, Sway, Heave Accelerations	Accelerometers on Gyroscopic Mount (Humphrey Motion Pack)	Operational
Visual Activity beneath ACIB	U/W Camera	Operational (repaired after damage by ice impact)
Voice Track	SE-8 Channel Recorder	Operational
Hydraulic Pump oil Temperature	Thermocouple	Deleted
	<u>SHIP</u>	
Port Notch cable Tension	Strain Gauged Tension Link	Non-Op
Stbd. Notch cable Tension	Strain Gauged Tension Link	Operational
Pitch and Roll	Pendula Pots	Non-Op
Fuel Consumption	Manually logged	—
3 Shaft rpm's	Magnetic Pick-up	Operational
Ship Speed	Doppler Microwave Radar	Operational
3 Shaft Torques	Strain gauges with Accurex FM Transmitter to get signal off rotating shafts	Operational
		Continued...

TABLE B1 continued...

PARAMETER	<u>SHIP</u> METHOD	STATUS
Port Forward and Reverse Thrust	Custom Thrust cells inside	Operational
Visual Recording of ship and ACIB	Camera mounted on top of bridge in an environmental housing	Operational
Time/Date information	Datum Time Date generator	Non-Op
Voice Track	28 Channel Recorder	Non-Op
Milling	Torque spikes detected by electrosonic circuits	Operational

ACIB Rise Height

The ultrasonic transducer system was put together on very short notice and was experimental in nature. Of the variety of problems encountered with the system, the major drawback leading to a non-operational system was the sonic transducer itself, which was not waterproof. Since then, however, we have encountered a commercially available system which meets our requirements built by Miltronics of Peterborough. In the future it is recommended that these units be used. They are both waterproof and inexpensive (\$600).

Port Notch Cable Tension

One of the two strainert tension links failed due to water seepage into the gauge area.

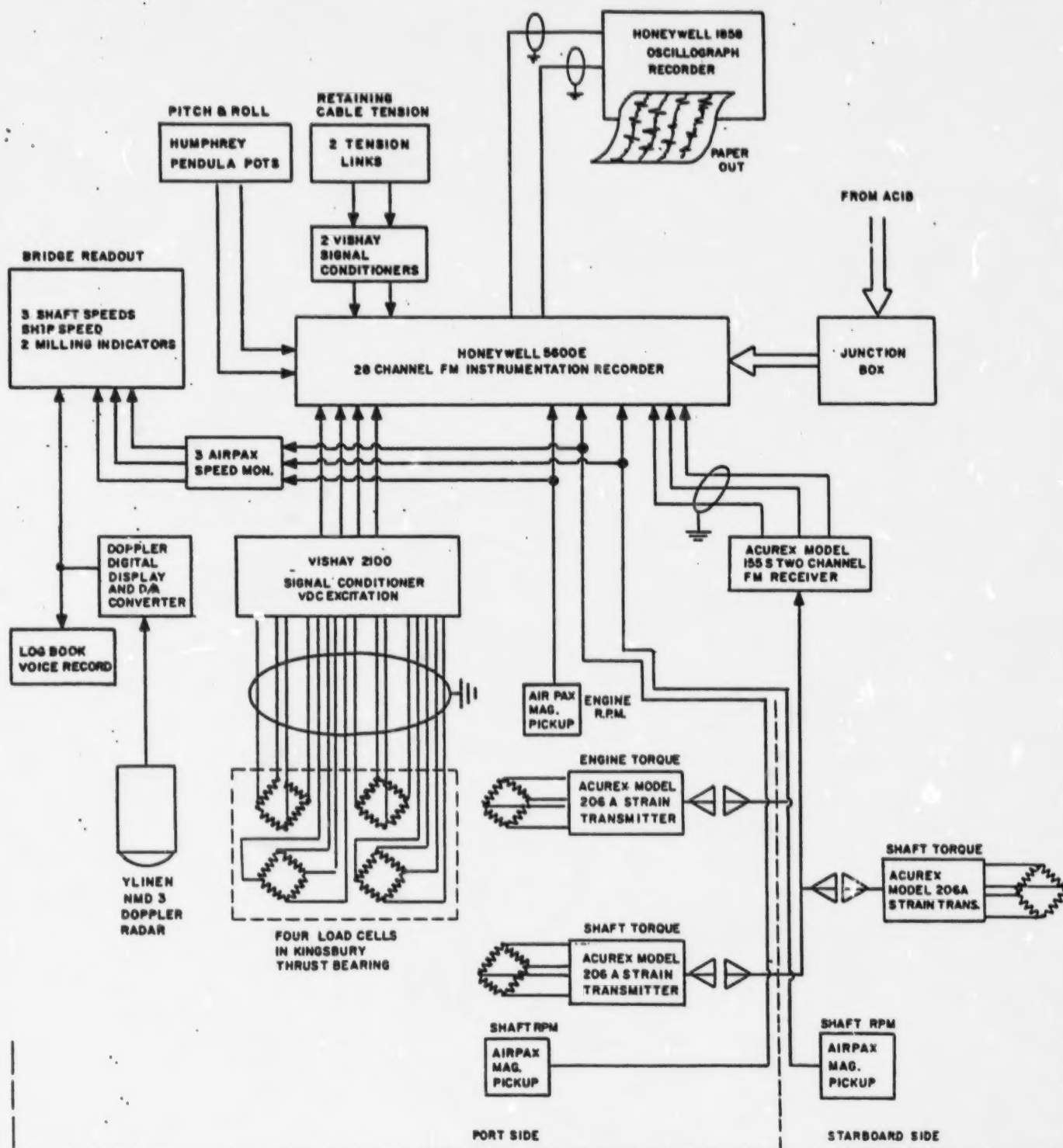
Ship Pitch and Roll

A malfunction of the pitch and roll pots in the Humphrey motions package mounted on the ACIB forced us to substitute them with the pots on the ship. As well the pots on the ship were more resistant than the Humphrey pots.

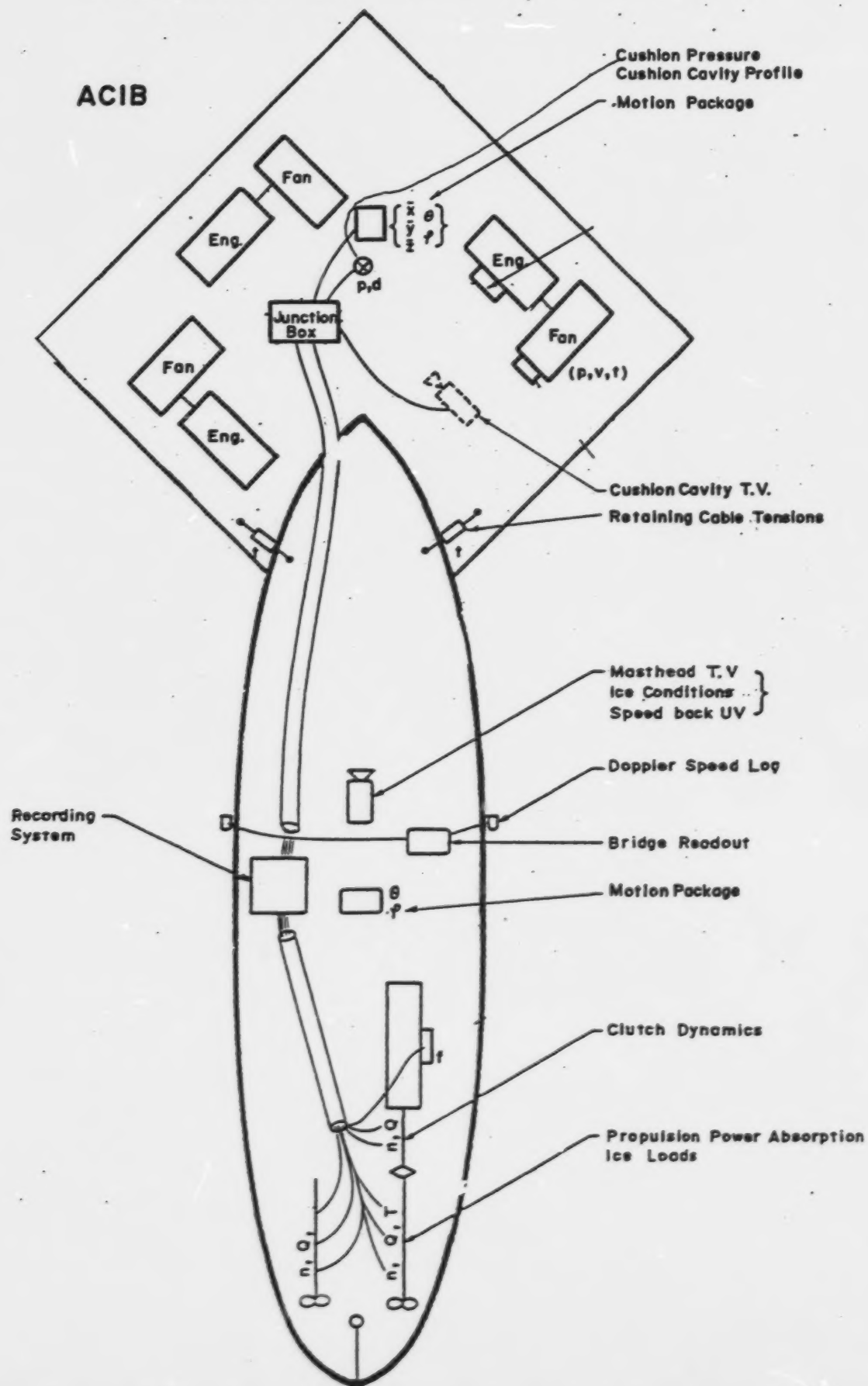
Time/Date Information

In order to record the fast code of the Datum Time Date Generator a direct record card is required. A failure of the Honeywell 28 channel recorder necessitated the exchange of the recorder for an operational one. When the new recorder arrived a direct record card was unavailable for the replacement and the voice record card malfunctioned preventing any voice record.

SHIP INSTRUMENTATION BLOCK DIAGRAM

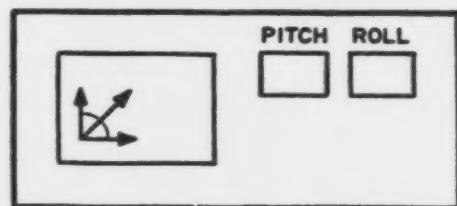


SCHEMATIC OF INSTRUMENTATION SYSTEM



ACIB INSTRUMENTATION BLOCK DIAGRAM

HUMPHREY VERTICALLY STABILIZED TRIAxIAL ACCELEROMETER



LOG
BOOK

JUNCTION BOX

DIRECT READING
PITCH & ROLL METERS

MULTICONDUCTOR
TO HOST SHIP

SURFACE WAVE MEASUREMENT & REFERENCE

FOUR SONIC
TRANSDUCERS

CUSHION PRESSURE

PRESSURE GAUGES

LOG BOOK

SIGNAL CONDITIONING
WHERE REQUIRED

HONEYWELL 1858
OSCILLOGRAPH
RECORDER

SE
8-CHANNEL
FM RECORDER

APPENDIX C

THRUST, VELOCITY AND RPM

THRUST VELOCITY AND RPM

Based on the results of previous and present tests, a relationship is included in this appendix that will be helpful to predict the thrust of the ALEXANDER HENRY ship if the RPM is known. This data has been gathered from a relatively steady condition of motion through ice of various thicknesses.

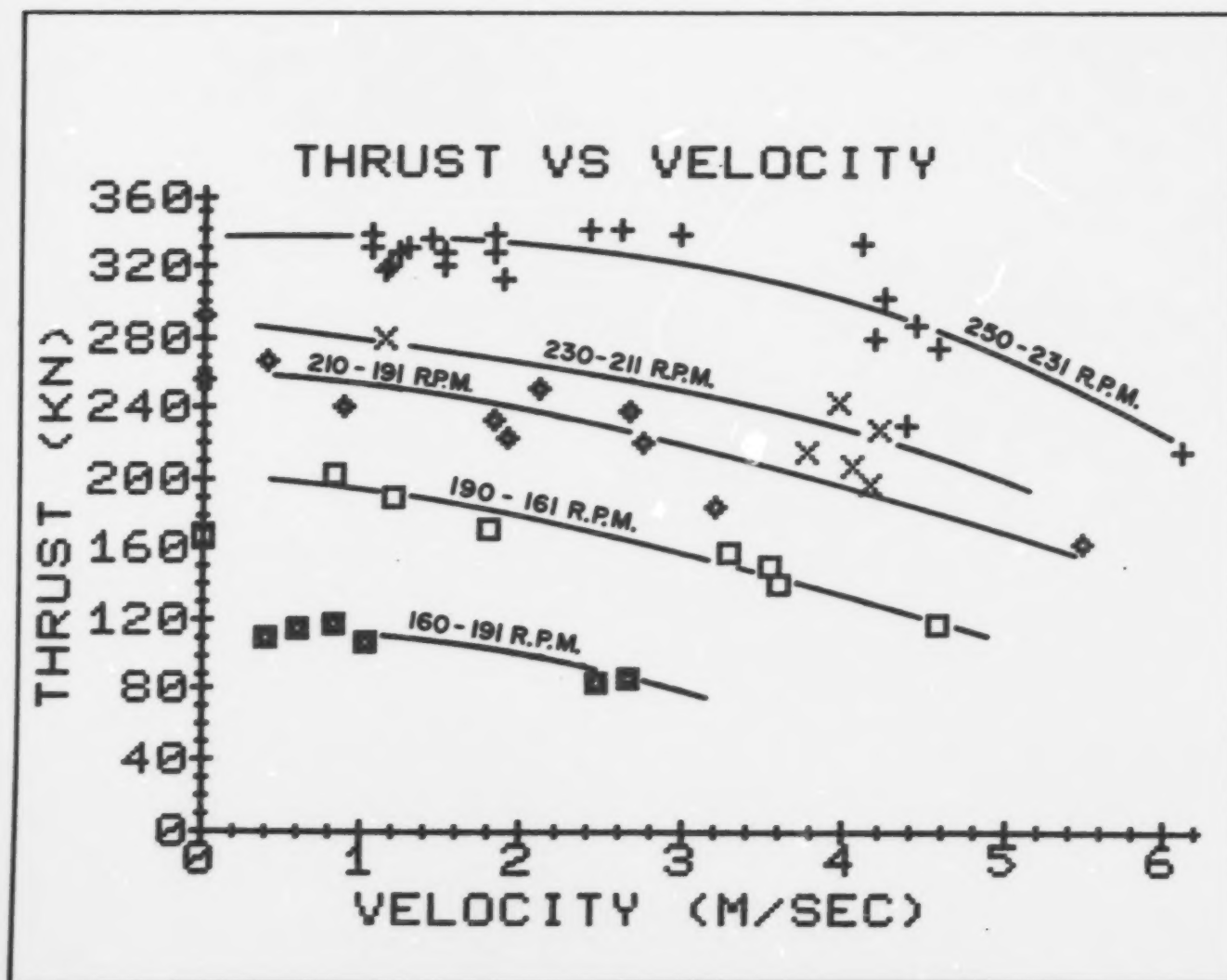


TABLE C-1
ALEXANDER HENRY VELOCITY AND THRUST FOR VARIOUS RPM

	VELOCITY		R P M			THRUST	
	(FT/SEC)	(M/SEC)	PORT	STBD	AVG	(LBS)	(KN)
1	10.50	3.20	203	201	202	41600	185
2	15.00	4.57	252	250	251	61600	275
3	3.40	1.04	136	129	133	23800	106
4	9.00	2.74	203	198	201	49500	221
5	13.70	4.18	244	250	247	62600	279
6	2.00	0.61	123	126	125	25500	114
7	6.90	2.10	205	200	203	56100	250
8	13.50	4.11	246	251	249	74800	334
9	2.70	0.82	138	126	132	26200	117
10	13.90	4.24	245	243	244	67700	302
11	0.00	0.00	210	210	210	65252	291
12	3.90	1.19	186	192	189	42128	188
13	2.70	0.82	182	183	183	45100	201
14	5.00	1.52	256	246	251	71800	320
15	6.00	1.83	203	202	203	52400	234
16	2.90	0.88	202	202	202	53800	240
17	5.00	1.52	246	252	249	73300	327
18	1.30	0.40	131	138	135	24400	109
19	5.90	1.80	174	180	177	38300	171
20	8.70	2.65	212	213	213	53100	237
21	14.60	4.45	254	248	251	64500	288
22	0.00	0.00	196	198	197	57200	255
23	6.20	1.89	199	200	200	50000	223
24	7.90	2.41	250	244	247	76600	342
25	9.70	2.96	255	247	251	75500	337
26	8.60	2.62	244	242	243	76600	342
27	3.80	1.16	241	240	241	71700	320
28	6.10	1.86	247	238	243	69900	312
29	3.70	1.13	244	238	241	71300	318
30	4.00	1.22	250	242	246	73500	328
31	6.00	1.83	244	241	243	75500	337
32	6.00	1.83	240	239	240	73300	327
33	3.50	1.07	241	237	239	76000	339
34	4.70	1.43	242	240	241	75300	336
35	1.30	0.40	201	200	201	59900	267
36	3.70	1.13	221	223	222	62800	280
37	3.50	1.07	246	237	242	74100	330
38	4.20	1.28	246	238	242	74100	330
39	0.00	0.00	182	186	184	37700	168
40	10.80	3.29	184	183	184	35600	159
41	12.30	3.75	209	213	211	48200	215
42	13.00	3.96	224	228	226	54500	243
43	0.00	0.00	60	88	74	7300	33
44	10.40	3.17	140	131	136	17600	78
45	15.00	4.57	172	177	175	26400	118
46	18.00	5.49	208	207	208	36700	164
47	20.00	6.10	241	240	241	48000	214
48	0.00	0.00	95	102	99	12200	54
49	8.70	2.65	129	140	135	19300	86
50	11.60	3.54	175	180	178	33800	151
51	13.30	4.05	209	215	212	46100	206
52	13.80	4.21	218	221	220	51000	227
53	0.00	0.00	63	85	74	4800	21
54	8.10	2.47	131	140	136	18600	83
55	11.80	3.60	177	180	179	31100	139
56	13.60	4.15	209	212	211	44000	196
57	14.40	4.39	229	232	231	51500	230

APPENDIX D

PITCH AND ROLL DATA

The calculation of the pitch and roll tests are included in this appendix. Twenty-one loading types were made resulting in various pitch and roll moments. The location of the loads is shown in Figure D.1 and are noted using letters from A to R. Twenty-two large concrete blocks were used for ballast. Each block weighed between 3.90 and 4.54 tonnes as shown in Table D.2. Table D.1 presents for each test the locations and the blocks used as well as the calculated pitch and roll moments.

FIGURE D.1

BALLAST WEIGHT LOCATION FOR PITCH AND ROLL TESTS

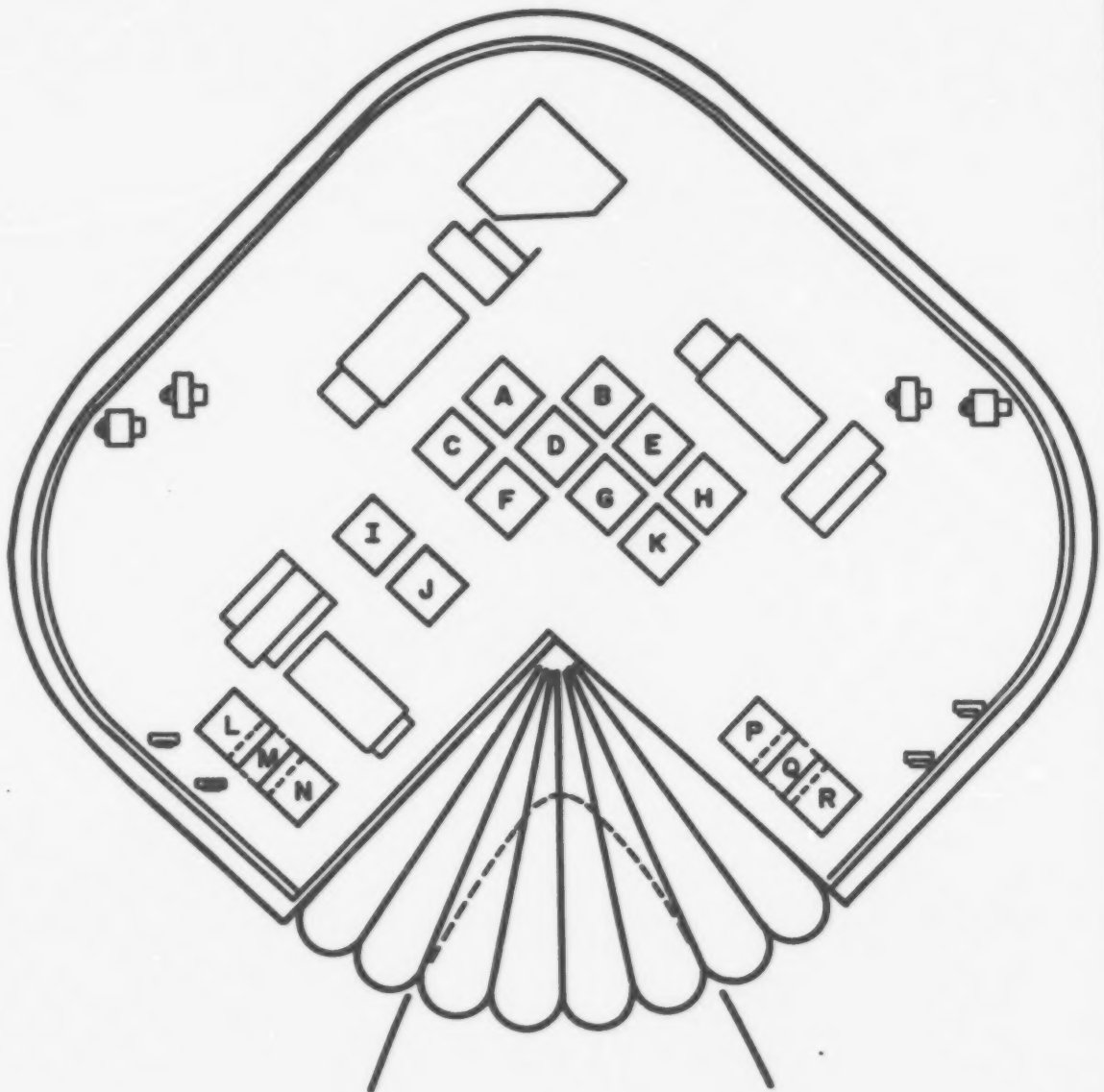


TABLE D.1
PITCH AND ROLL TESTS

TEST #	BLOCK #	LOCATION #	MOMENTS(TONNES/METRES)		COMMENTS
			PITCH	ROLL	
1	1	R	23.27	28.56	ACIB level and total ballast is 15.88 tonnes
	2	P	19.19	24.54	
	3	N	23.62	-23.66	
	4	L	19.33	-27.95	
	Total Moment		85.41	1.49	
2	Move Block 3 to Location R		85.17	53.83	
3	Move Block 4 to Location P		84.94	106.22	
4	1	R	23.27	28.56	
	2	A	-11.29	- 3.19	
	3	B	-11.51	6.71	
	4	N	23.62	-23.66	
			24.09	8.42	
5	5	L	18.99	-27.46	
	6	P	19.62	25.09	
	7	Q	21.61	27.03	
	8	M	22.24	-26.71	
	9	E	- 7.26	13.17	
	10	D	- 5.98	1.86	
	11	D	- 6.04	1.88	
	Plus test #3		24.09	8.42	
Total Moment		87.27	23.28		
6	Move 7 from Q to R and Move 8 from M to P		86.99	77.45	
7	Move 4 from N to Q		84.61	127.67	
8	Move 4 from Q to N Move 8 from P to A Move 7 from R to B		20.07	26.50	

TABLE D.1 - Page 2

9	I	R	23.27	28.56	Total ACIB load is 68.78 tonnes
	2	A	-11.29	- 3.19	
	3	B	-11.51	6.71	
	4	N	23.62	-23.66	
	5	L	18.99	-27.46	
	6	P	19.62	25.09	
	12	M	22.24	-26.71	
	13	R	23.26	28.56	
	14	I	0	-14.69	
	15	H	- 2.08	15.88	
	16	K	2.82	11.12	
	17	C	- 6.53	- 7.75	
	7	B	-11.63	6.83	
	8	A	-11.72	- 3.29	
	9	E	- 7.26	13.17	
	10	D	- 5.98	1.88	
	11	D	- 6.04	1.86	
Total Moment			59.78	32.91	
10	Move 12 from M to P		57.31	84.90	
11	Move 4 from N to Q		54.93	135.12	
12	Move 4 from Q to N Move 12 from P to E Move 13 from R to C		1.38	35.48	
13	Test 11		1.38	35.48	ACIB total load is 88.94 tonnes
	18	M	21.48	-25.81	
	19	R	23.50	28.85	
	20	F	-1.39	- 2.37	
	21	K	2.88	11.37	
	22	I	0	-14.62	
Total Moment			47.85	32.90	
14	Move 18 from M to P		45.47	83.13	
15	Move 4 from N to F		20.50	104.49	
16	Move 4 from F to N		45.47	83.13	
17	Move 18 from P to F		25.02	56.41	
18	Move 19 from R to L		20.95	- 0.53	
19	Move 18 from F to N		45.92	-21.87	
20	Move 18 from N to A Move 4 from N to B		-24.07	28.98	
21	Move 4 from B to N Move 19 from L to N Move 18 from A to Q		47.85	33.21	

TABLE D.2

BLOCK #	MASS (Tonnes)
1	3.95
2	3.99
3	3.97
4	3.97
5	3.90
6	4.08
7	4.04
8	4.11
9	4.54
10	4.04
11	4.08
12	4.11
13	3.95
14	4.08
15	3.92
16	3.97
17	4.08
18	3.97
19	3.99
20	4.08
21	4.06
22	4.06

APPENDIX E

OSCILLOGRAPH RECORDS OF RUNS WHERE
ICEBREAKING WAS OBSERVED

(The Originals are available at Arctec Canada
on O'Graph and on tape)

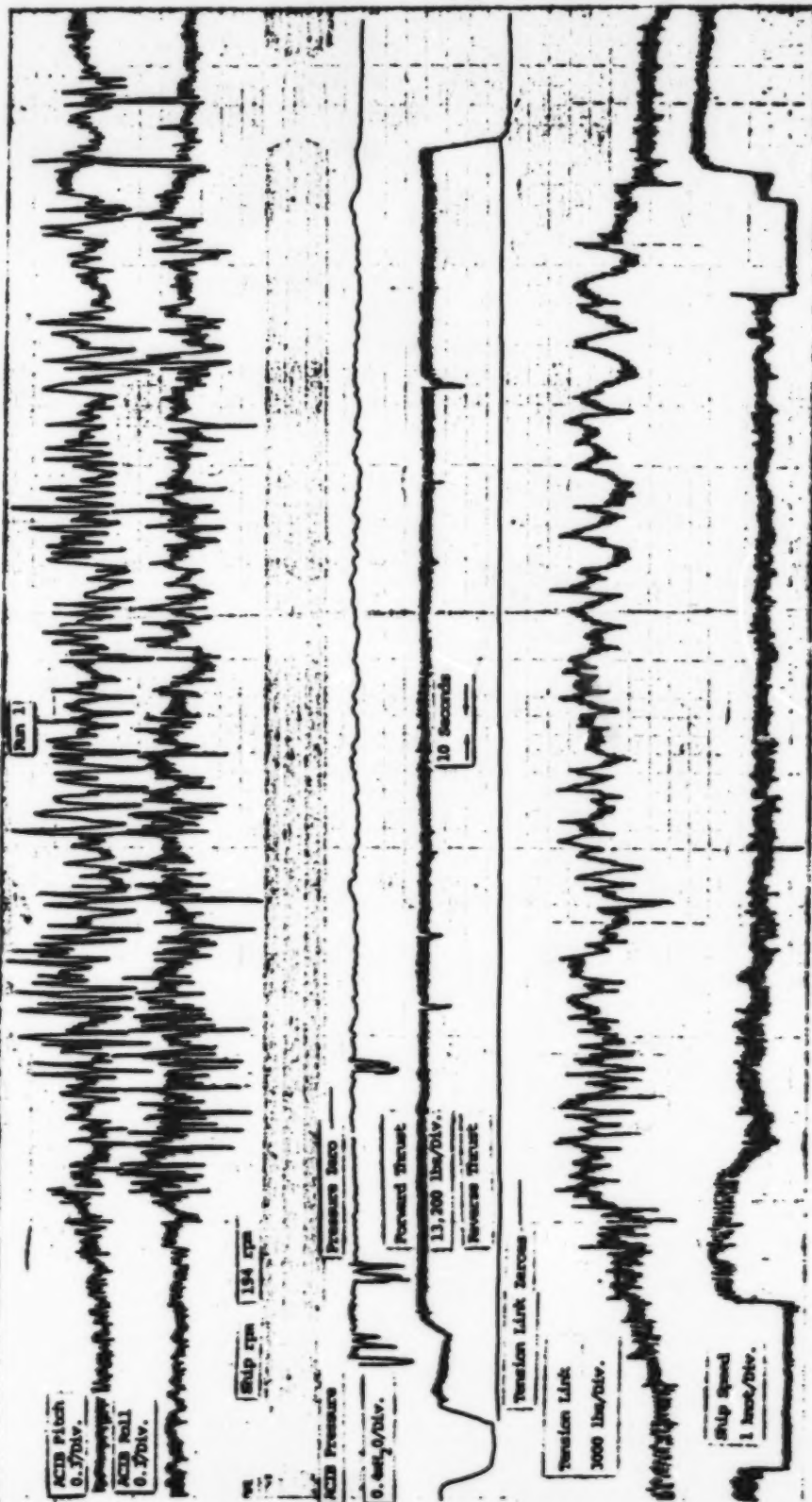
TABLE D.2

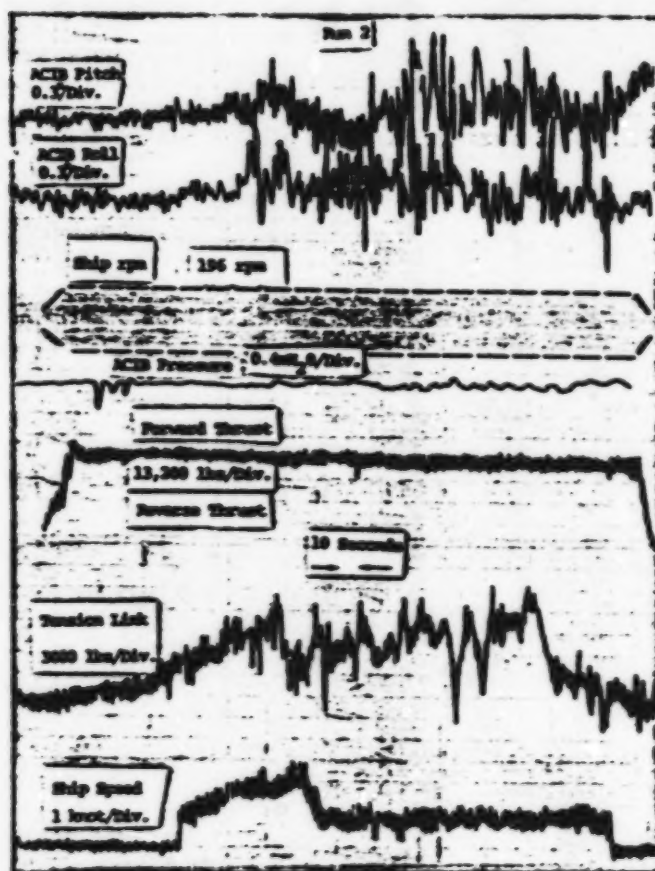
BLOCK #	MASS (Tonnes)
1	3.95
2	3.99
3	3.97
4	3.97
5	3.90
6	4.08
7	4.04
8	4.11
9	4.54
10	4.04
11	4.08
12	4.11
13	3.95
14	4.08
15	3.92
16	3.97
17	4.08
18	3.97
19	3.99
20	4.08
21	4.06
22	4.06

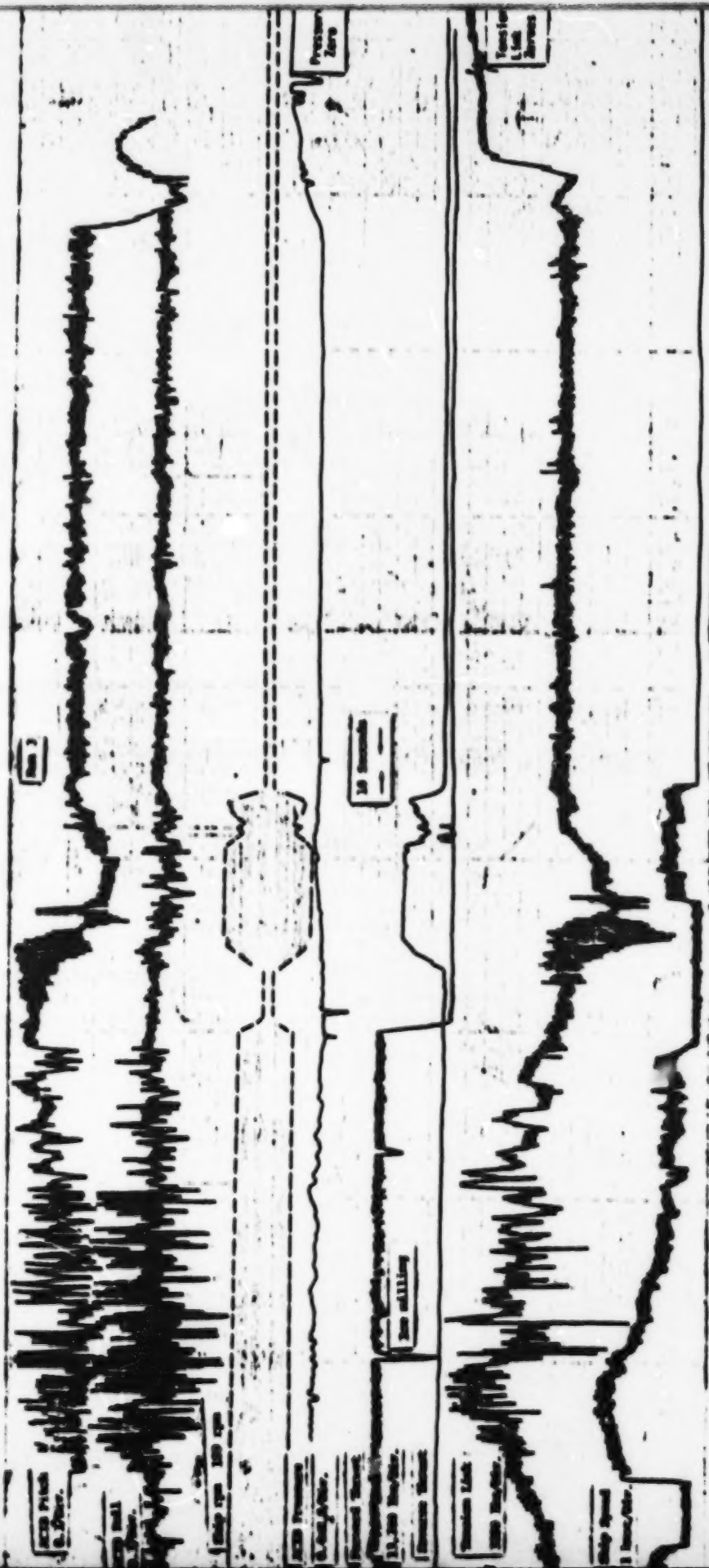
APPENDIX E

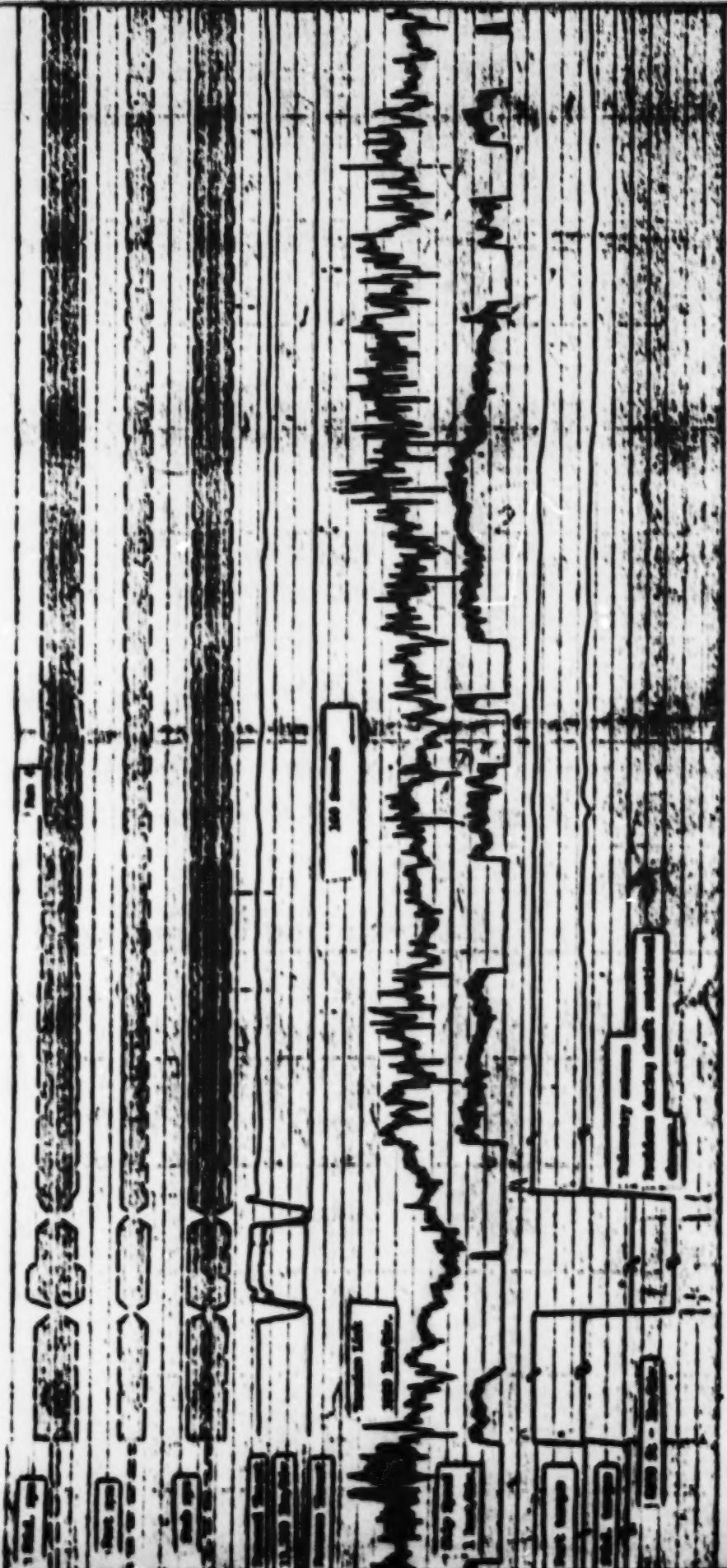
OSCILLOGRAPH RECORDS OF RUNS WHERE
ICEBREAKING WAS OBSERVED

(The Originals are available at Arctec Canada
on O'Graph and on tape)









APPENDIX F

TEMPERATURE AND AIR PRESSURE DATA FOR THUNDER BAY HARBOUR

TABLE F.1

TEMPERATURE AND AIR PRESSURE DATA FOR THUNDER BAY HARBOUR

DAY	TEMPERATURE (°C)	AIR PRESSURE (kPa) *
Mar 13 1982	-1.0	96.04
14	-2.6	99.81
15	+0.2	99.16
16	+0.1	98.49
17	+1.2	98.99
18	-3.7	98.79
19	-8.5	100.44
20	-4.8	99.35
21	+1.3	98.52
22	-1.2	99.19
23	-1.7	97.71
24	+0.7	97.40
25	-0.9	97.37
26	-11.1	100.57
27	-11.5	101.03
28	-5.7	99.26
29	+3.2	99.39
30	+2.1	97.10
31	+0.9	96.89
April 14 1982	+3.3	99.15
15	+6.9	98.20
16	+5.7	98.30
22	+5.8	99.77
23	+13.0	98.50
24	+11.8	97.93
25	+9.8	98.44
26	+3.2	99.83
27	+3.8	100.51
28	+6.7	100.20
29	+7.3	100.19

* Air Pressure was taken at 1:00 pm at the Weather Station.

POOR

QUALITY

ORIGINAL